A Rhapsody in Blue:
Dark Matter searches with the Fermi LAT

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Physics Colloquium

GRAPPA
GRavitation AstroParticle Physics Amsterdam
NWO

Overview

- **Introduction**
  - How and why searching for Dark Matter?
- **Indirect Dark Matter Searches**
  - Anti-protons
  - Gamma rays (lines, dwarfs & the Galactic center)
- **Outlook & Conclusions**

The Dark Matter Problem

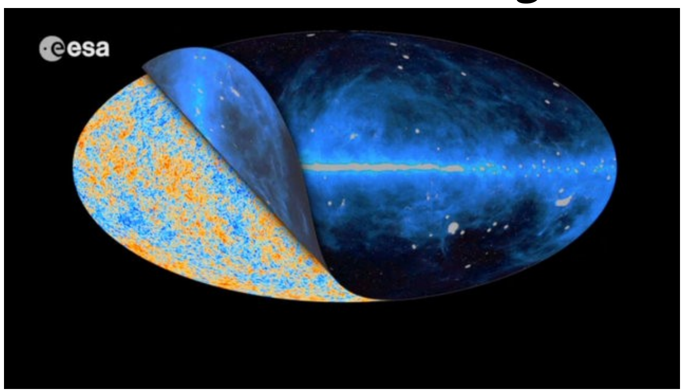
We observe 5X more **Dark Matter** in the Universe than **Baryons** (Atoms, Planets, Galaxies) …

… but its true nature remains unknown

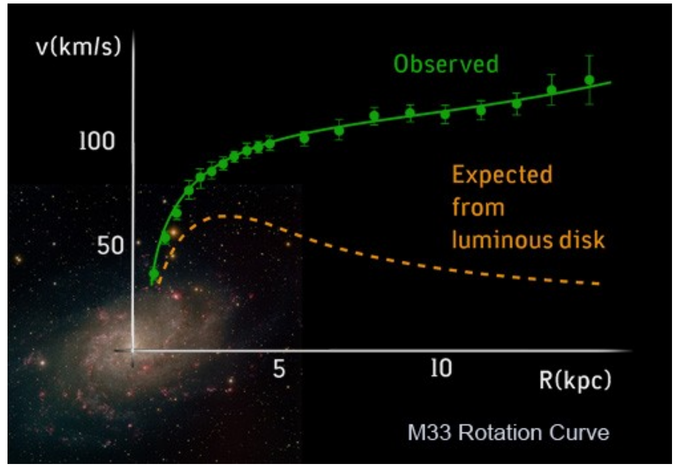
Evidence for dark matter is omnipresent

Evidence for the existence of **non-baryonic** dark matter in the Universe comes from gravitational observations at different length scales (from sub-galactic to cosmological scales).

Cosmic microwave background

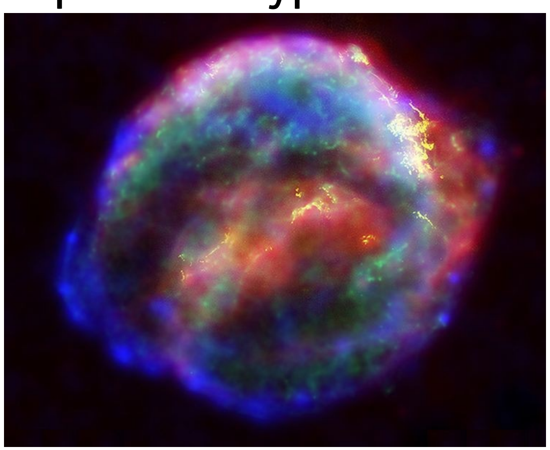


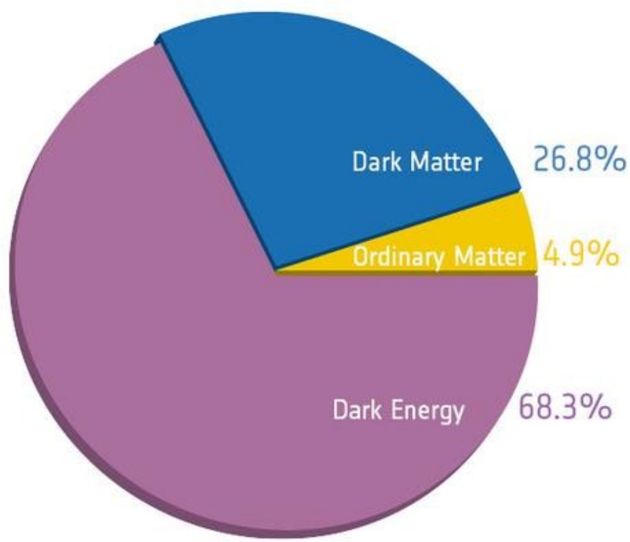
Galaxy rotation curves



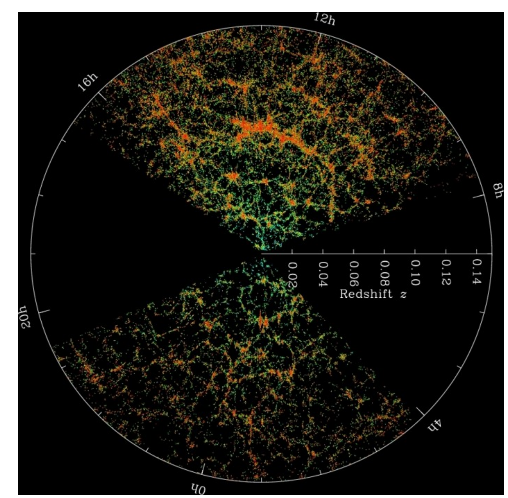
Galaxy clusters

Supernova Type 1A





Large scale structures



85% of all matter in the Universe is **dark** and **non-baryonic**.

What we know

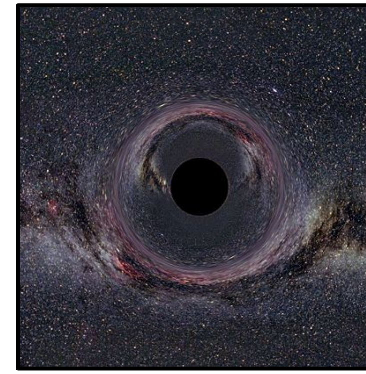
About 80 years after the first discovery of dark matter by Fritz Zwicky and others, we can now bracket its particle mass to **within 80 orders of magnitude**.

Uncertainty principle (if DM is bosonic)

Hu+ 2000

MACHO searches (massive compact halo objects)

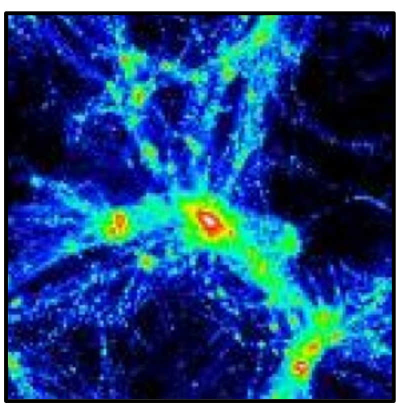
$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{50}\mathrm{GeV}$$



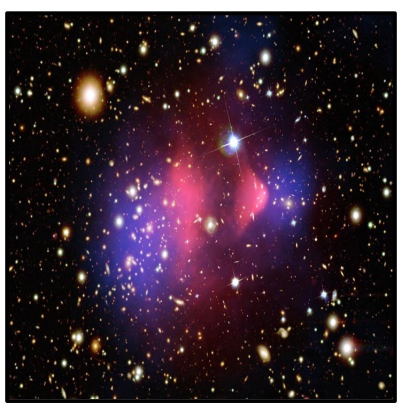
Tisserand+ 2007

Up to now, there are only various upper and lower limits:

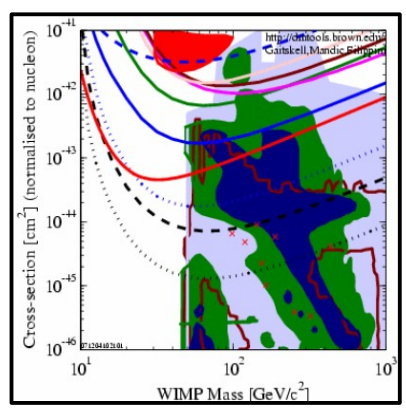
cold:
negligible velocity dispersion

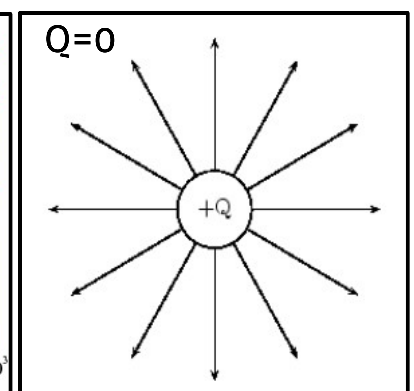


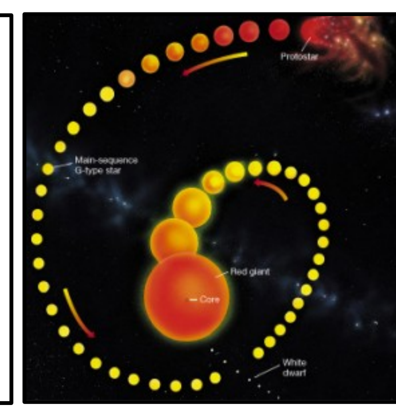
collisionless:
negligible self-interaction



weakly coupled:
negligible interaction with the rest of the world







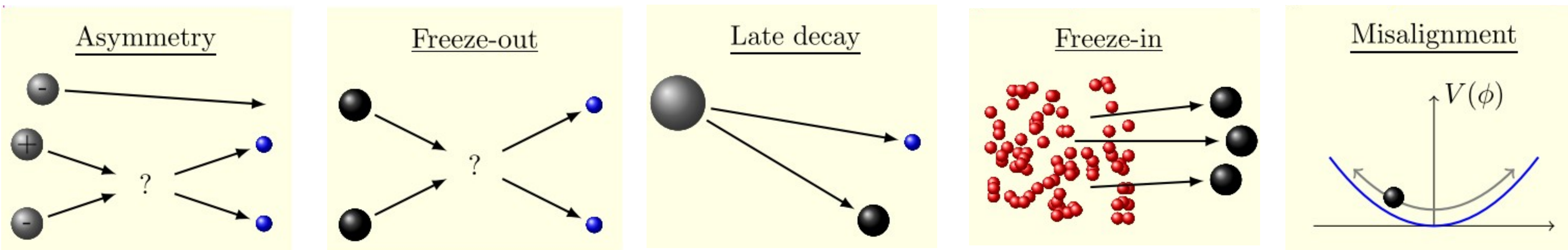
The two corner stones of speculation about DM

DM was produced in the early Universe

Main constraint: observed dark matter density and temperature.

Many ideas for production mechanisms:

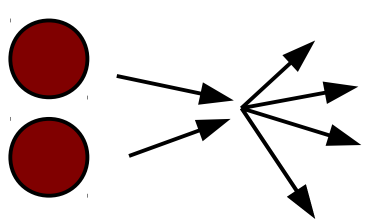
Electro-weakly coupled ⟷ Extremely weakly coupled



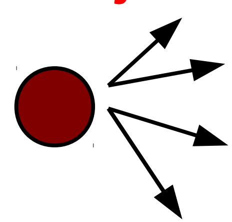
DM is still around today

Protected by symmetry in Lagrangian, which might be slightly broken.

Self-annihilation

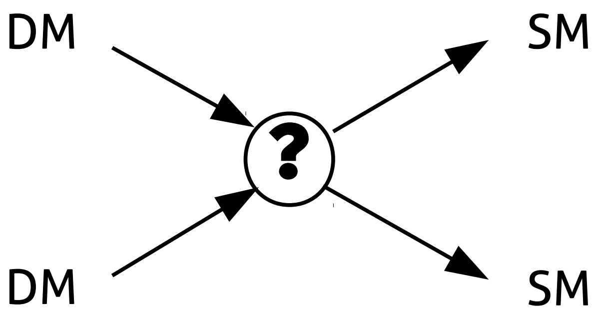


Decay on cosmological time-scales



$$\tau_{\mathrm{DM}} \gg \tau_{\mathrm{Universe}}$$

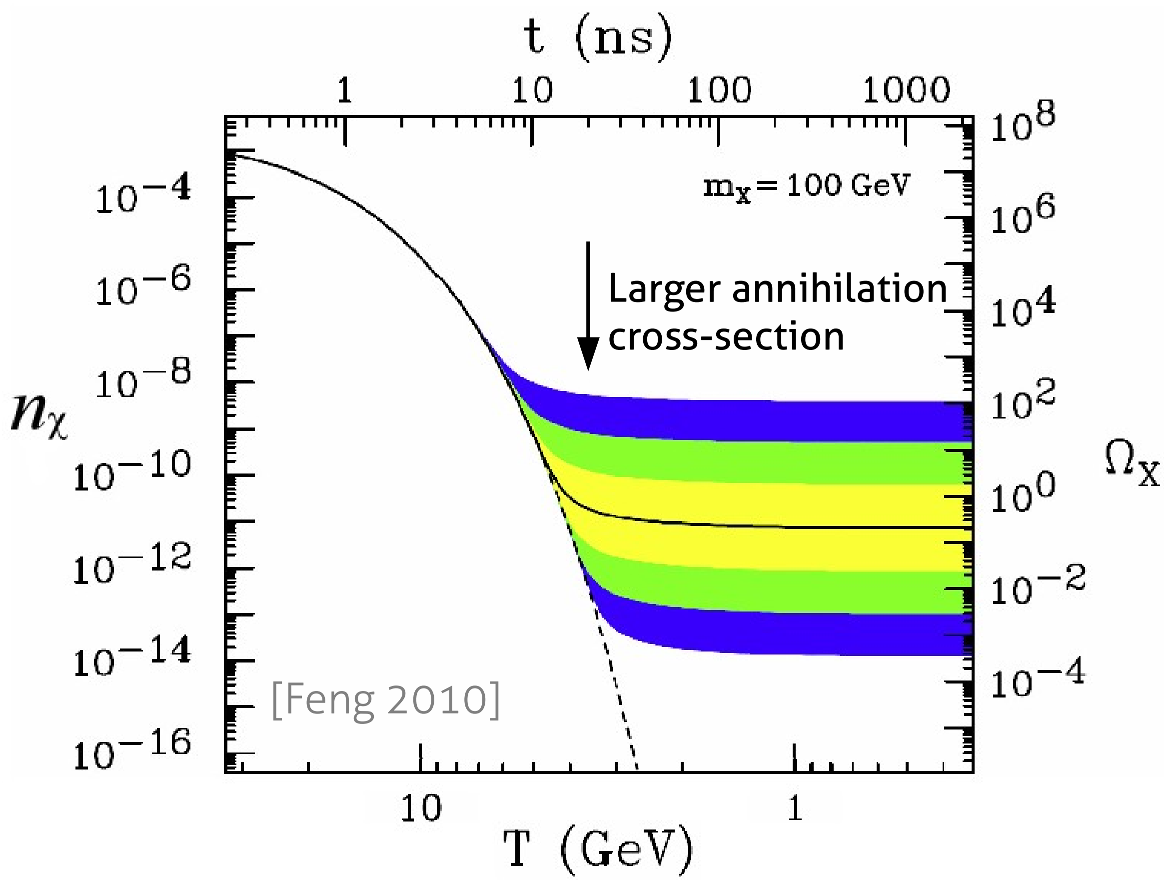
Weakly Interacting Massive Particles (WIMPs) in the early Universe: The freeze-out mechanism



Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Velocity-averaged annihilation cross-section in early Universe is fixed by observed mass density of DM.



$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma v \rangle}$$

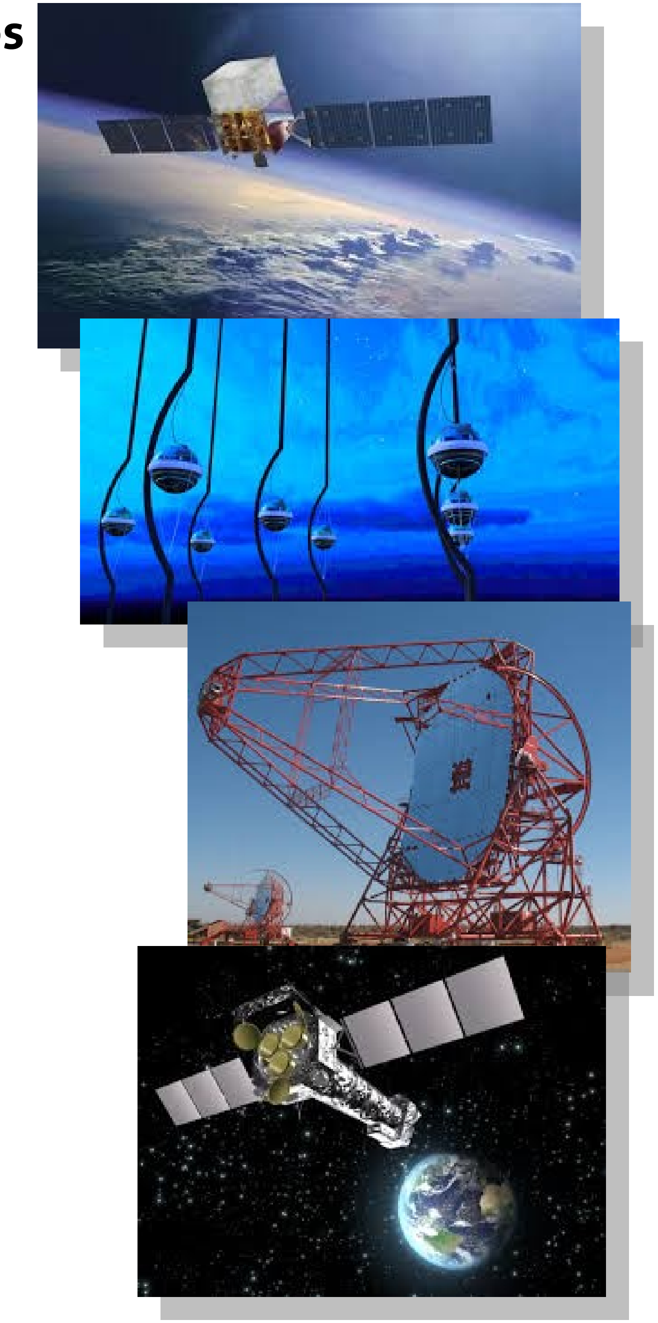
This is very close to experimental sensitivities!

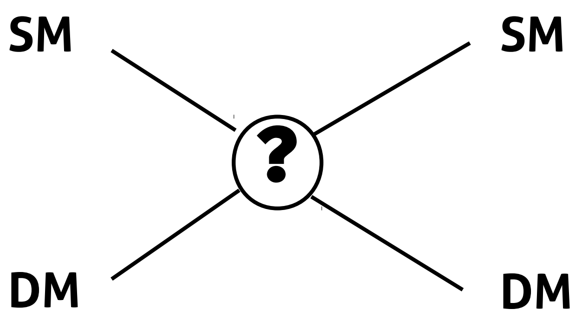
This provides a rough estimate for annihilation rate of DM particles today.

Enormous effort to search for WIMP dark matter

Direct DM searches (DM scattering)

Indirect DM searches (DM annihilation)





Searches at particle colliders (DM production)

Indirect Searches for Dark Matter

Many false alarms?

"No testimony is sufficient to establish a miracle, unless the testimony be of such a kind, that its falsehood would be more miraculous than the fact which it endeavors to establish." (David Hume)

Space » 60-Second Space

By Clara Moskowitz | September 24, 2014

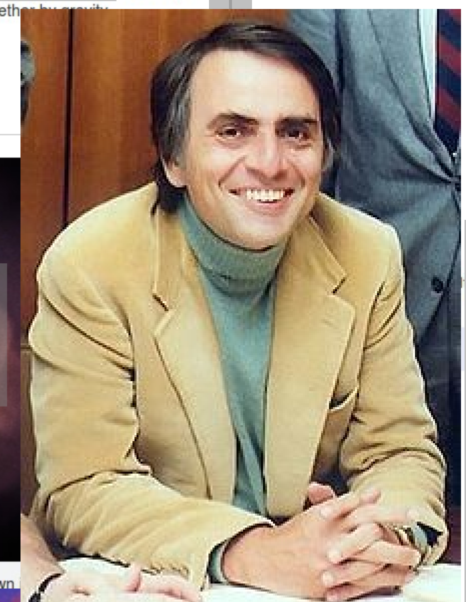
Fermi data tantalize with new clues to dark matter: Gamma rays from center of Milky Way galaxy

Date: April 3, 2014

Source: NASA

Summary: A new study of gamma-ray light from the center of our galaxy makes the strongest case to date that some of this emission may arise from dark matter, an unknown substance making up most of the material universe. Using publicly available data from NASA's Fermi Gamma-ray Space Telescope, independent scientists at the Fermi National Accelerator Laboratory (Fermilab), the Harvard-

"Extraordinary claims require extraordinary evidence." (Carl Sagan)



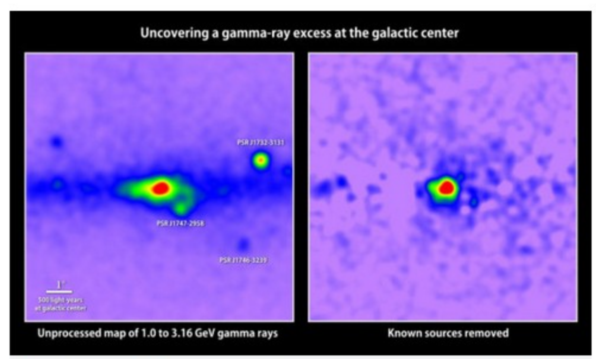
RELATED TOPICS

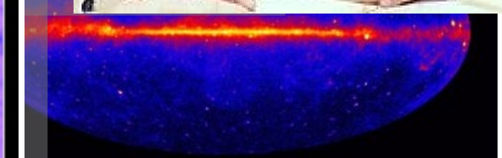
Space & Time
- Dark Matter
- Astrophysics
- Astronomy

Matter & Energy
- Quantum Physics
- Physics
- Nuclear Energy

RELATED TERMS

FULL STORY





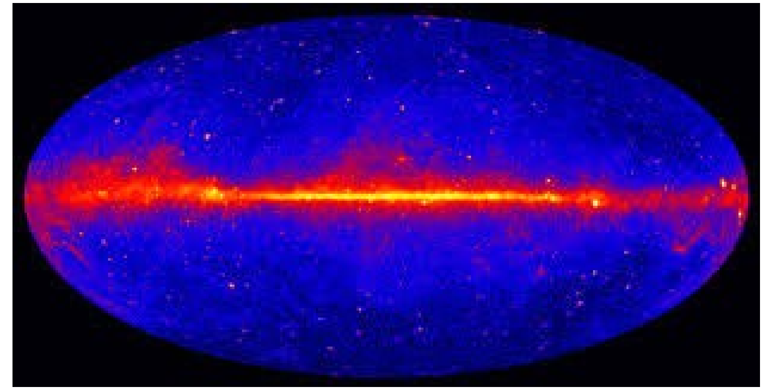
hints of dark matter lurking in Fermi's view of the sky?

"Don't cry wolf!"

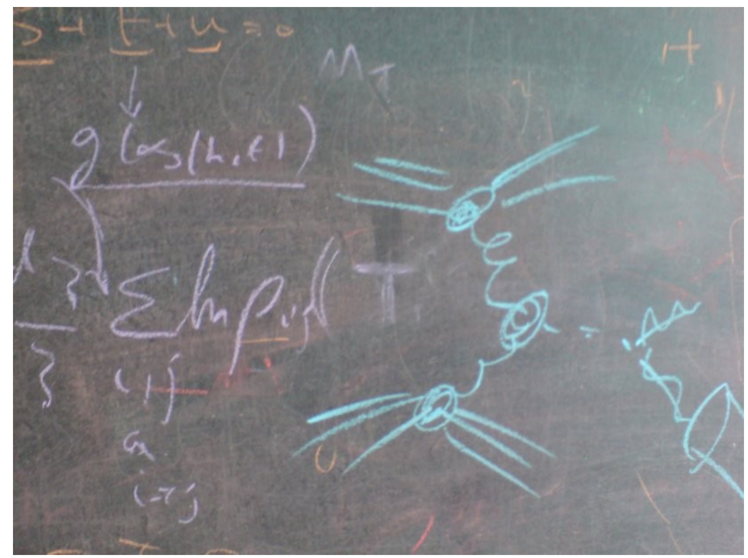
(Nature comment by Jan Conrad, Stockholm University)

Why are indirect searches interesting?

Astrophysical uncertainties are *large*, *but not arbitrary*.

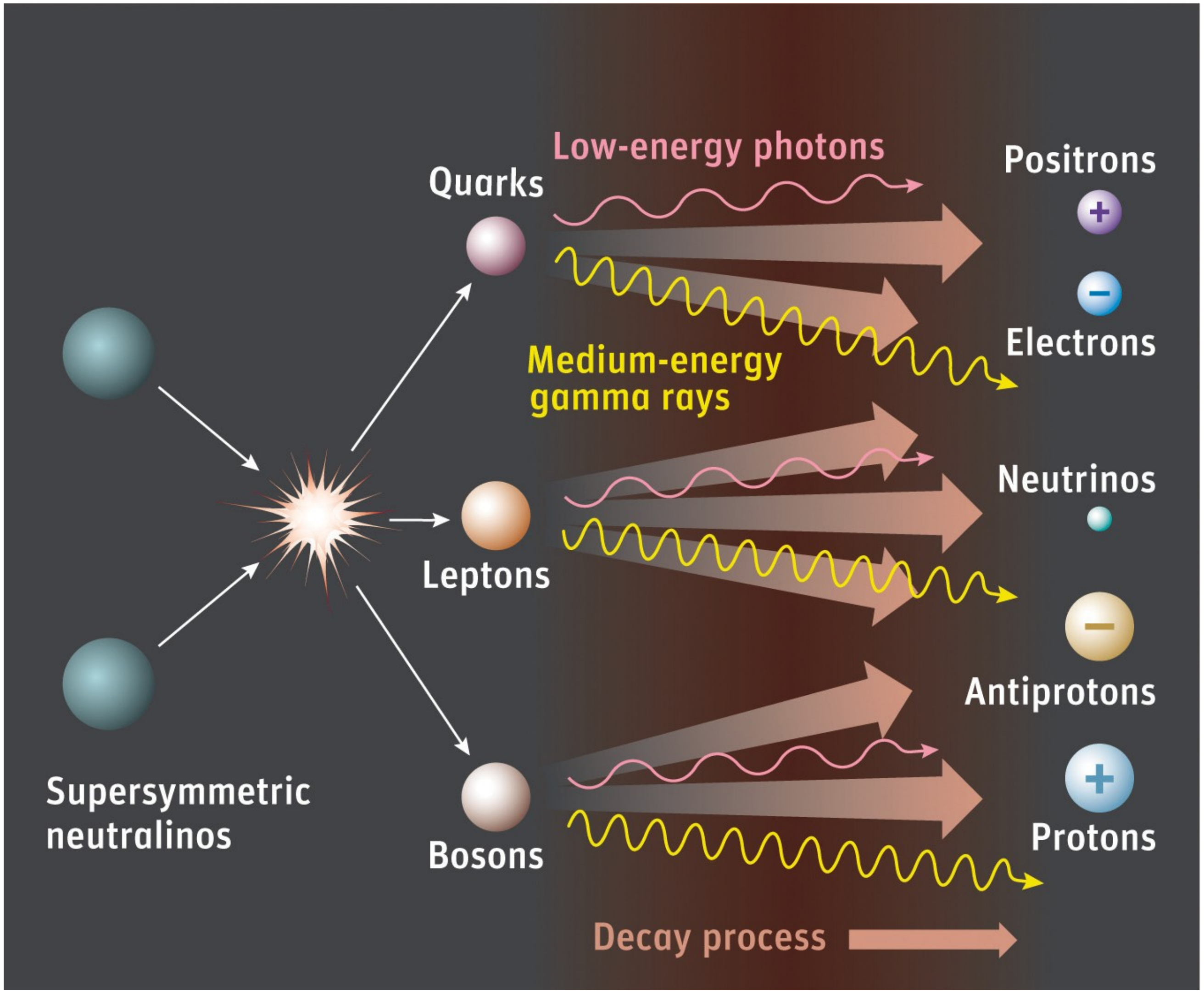


Dark matter model uncertainties are *infinite*, *but even less arbitrary*.



Bonus: While understanding “backgrounds”, one understands something about the Universe.

Dark Matter annihilation



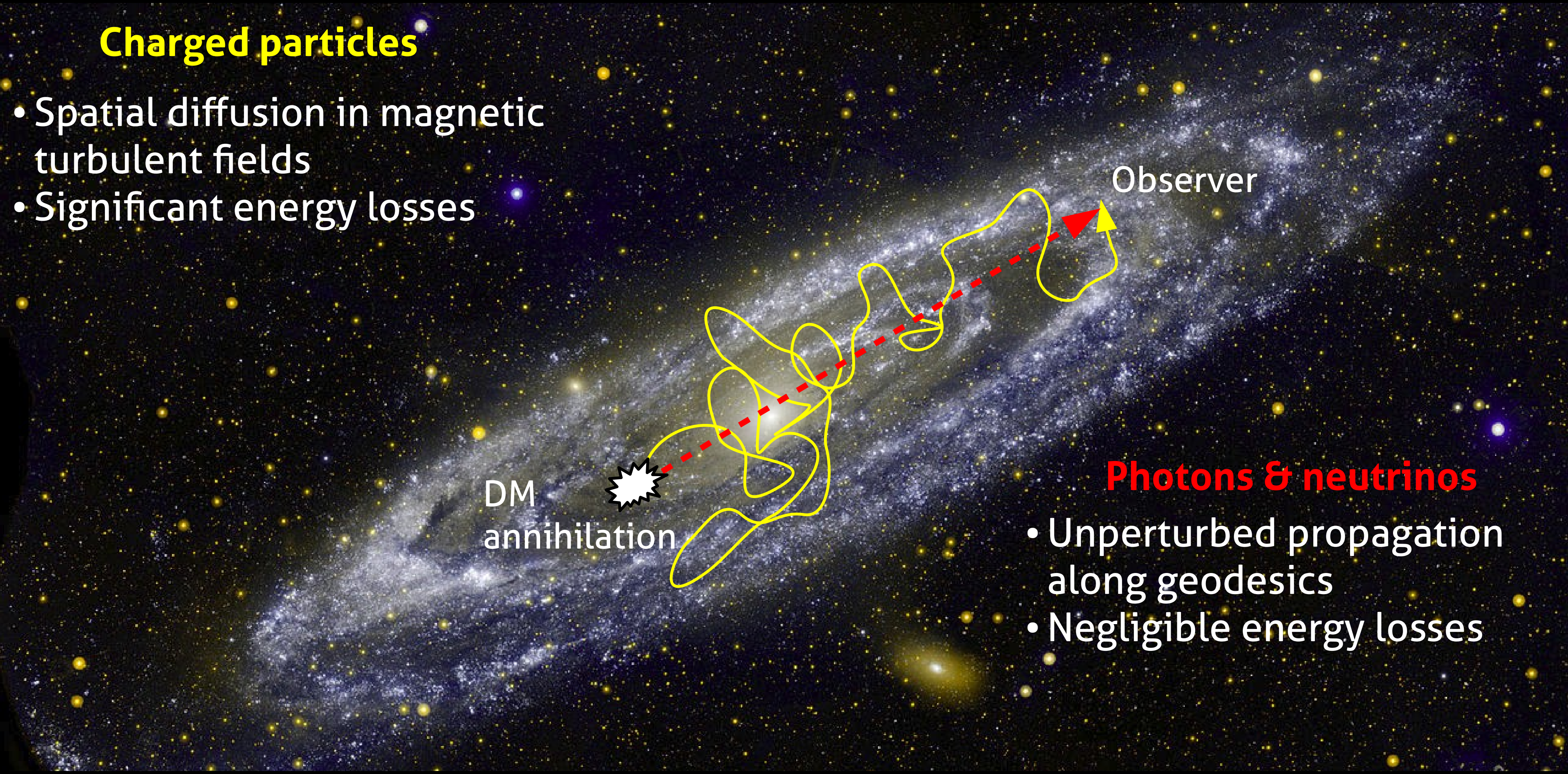
Stable standard model particles define possible search channels

- Electrons, positrons
- Protons, **anti-protons**
- **Photons**
- Neutrinos

DM annihilation products in the Milky Way

Injection rate of DM annihilation products

$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle \sigma v \rangle \rho_{\rm DM}^2}{2 m_{\rm DM}^2} \frac{dN_X}{dE}$$



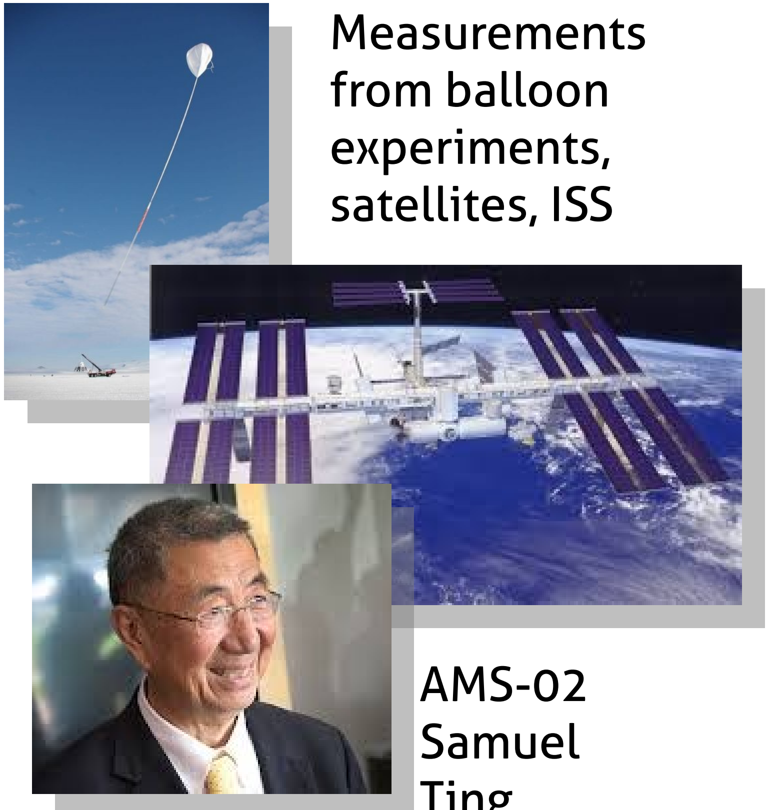
Charged particles

- Spatial diffusion in magnetic turbulent fields
- Significant energy losses

Photons & neutrinos

- Unperturbed propagation along geodesics
- Negligible energy losses

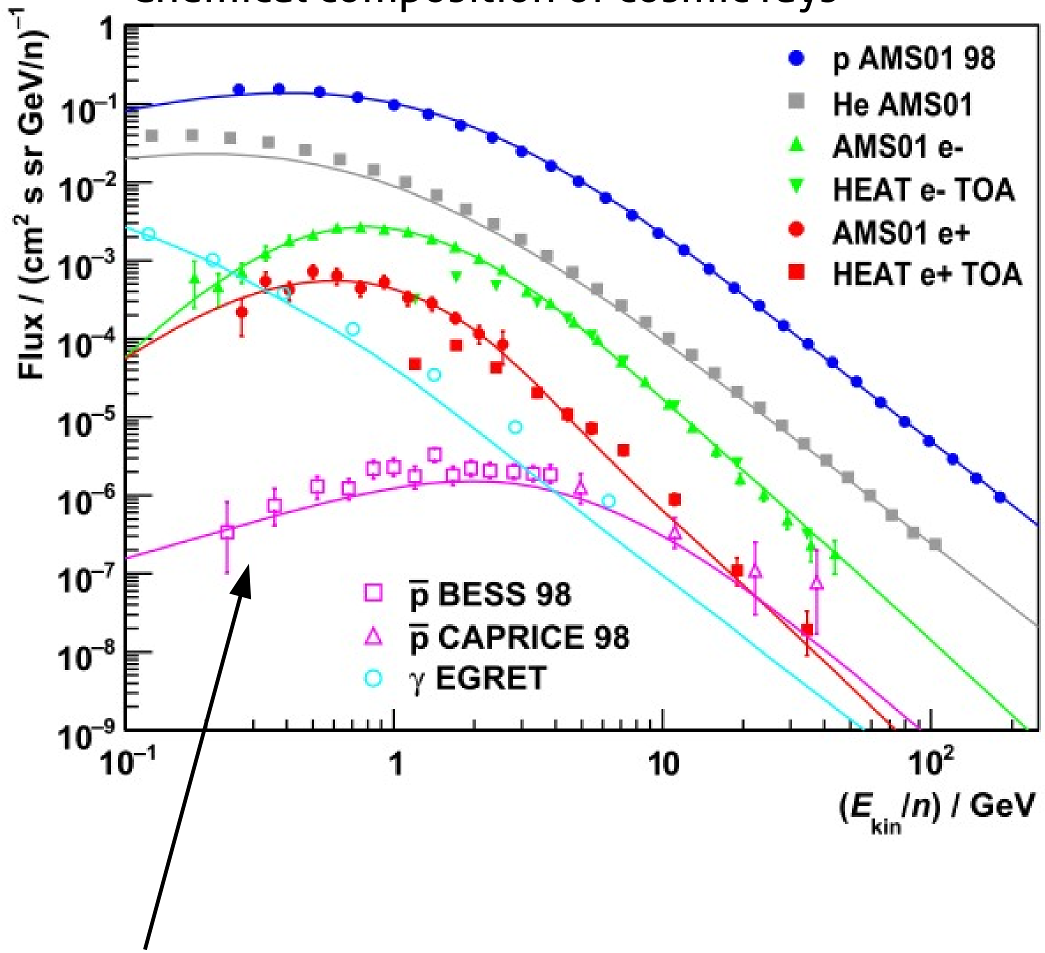
Dark Matter searches with anti-protons



Measurements from balloon experiments, satellites, ISS

AMS-02 Samuel Ting

Chemical composition of cosmic rays



Why anti-protons?

- Very low backgrounds

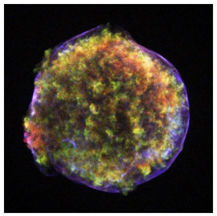
Observed: One antiproton per 100-10000 protons

- **Backgrounds extremely* well understood**

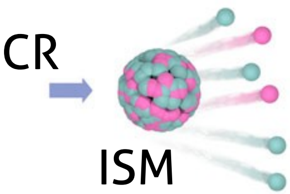
*up to a factor of two

The "grammage" matters

Two sources for cosmic rays

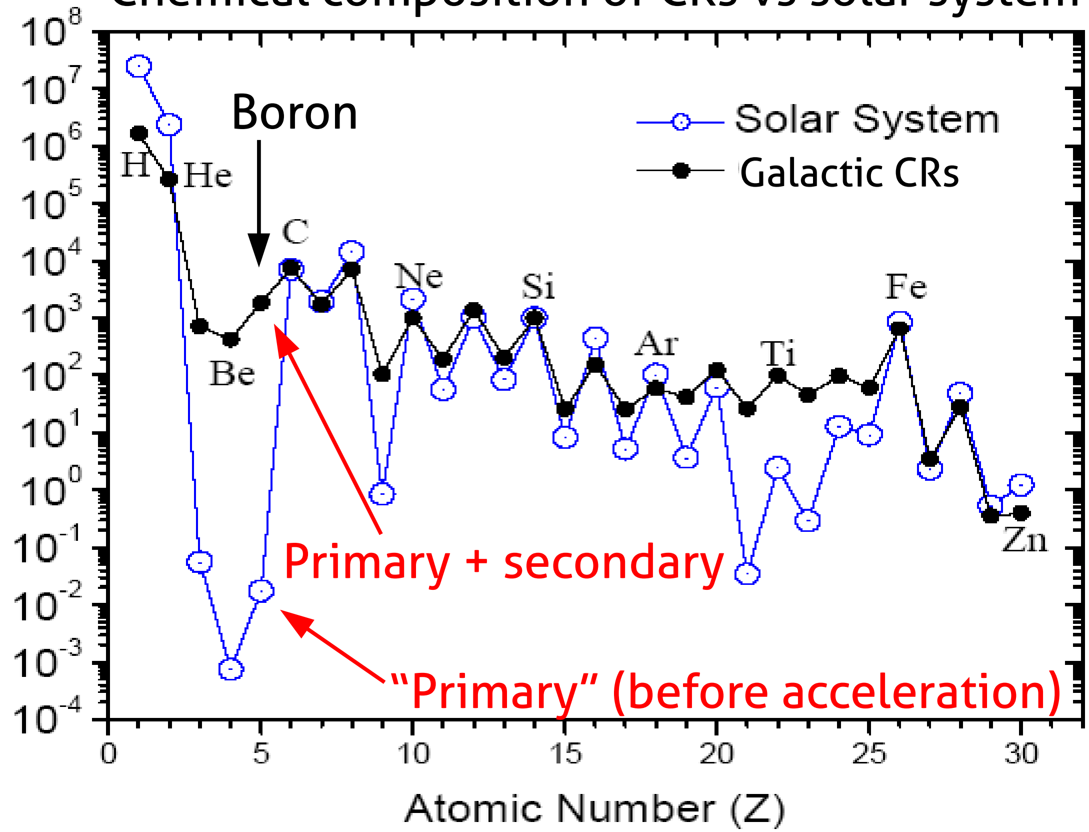


Primary cosmic rays
from supernova
remnants (likely)

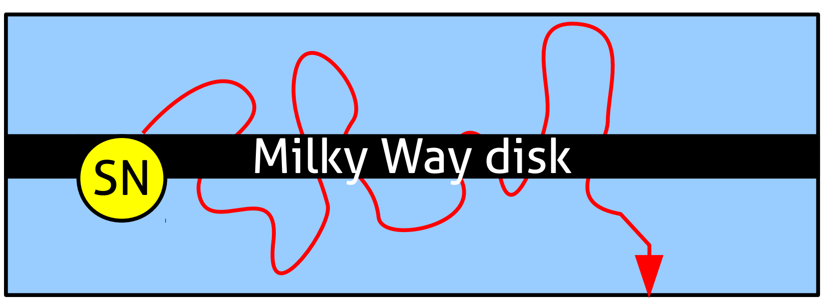


Secondary cosmic rays
from spallation etc

Chemical composition of CRs vs solar system



Diffusion in a box



Total grammage (column density along propagation path)

$$G_{\text{total}} = n_{\text{crossings}} G_{\text{disk}} \sim \mathcal{O}(10 \text{ g cm}^{-2})$$

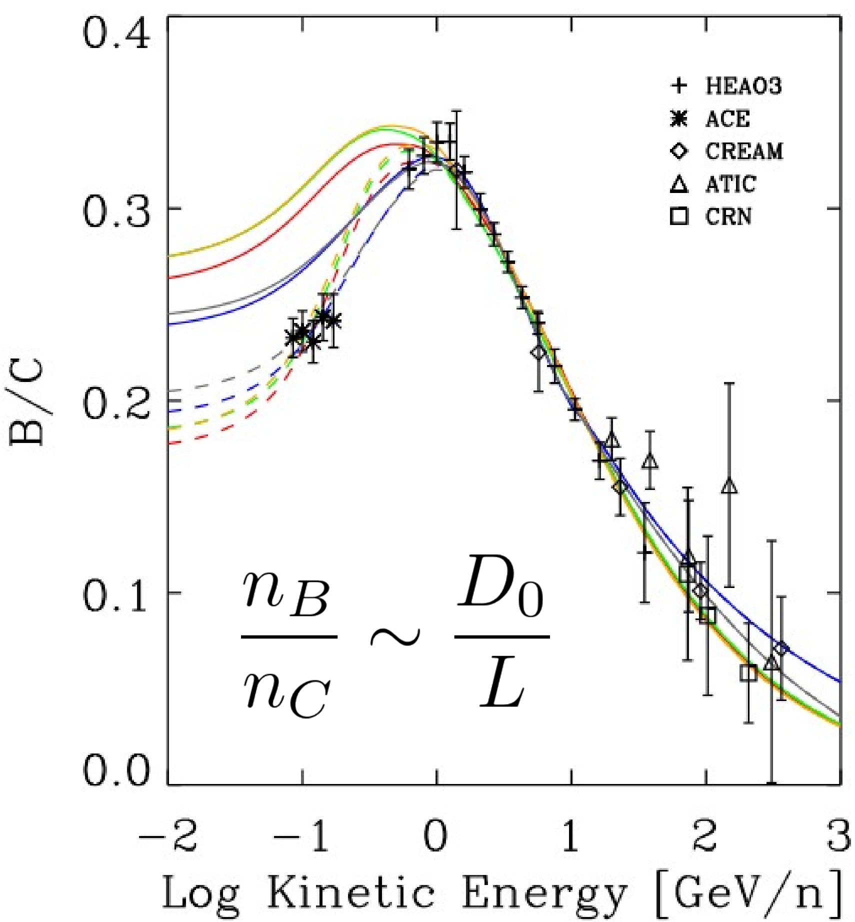
Secondary Boron: $n_B = n_C \sigma(C \to B) \cdot G_{\text{total}} \qquad \Rightarrow G_{\text{total}}$

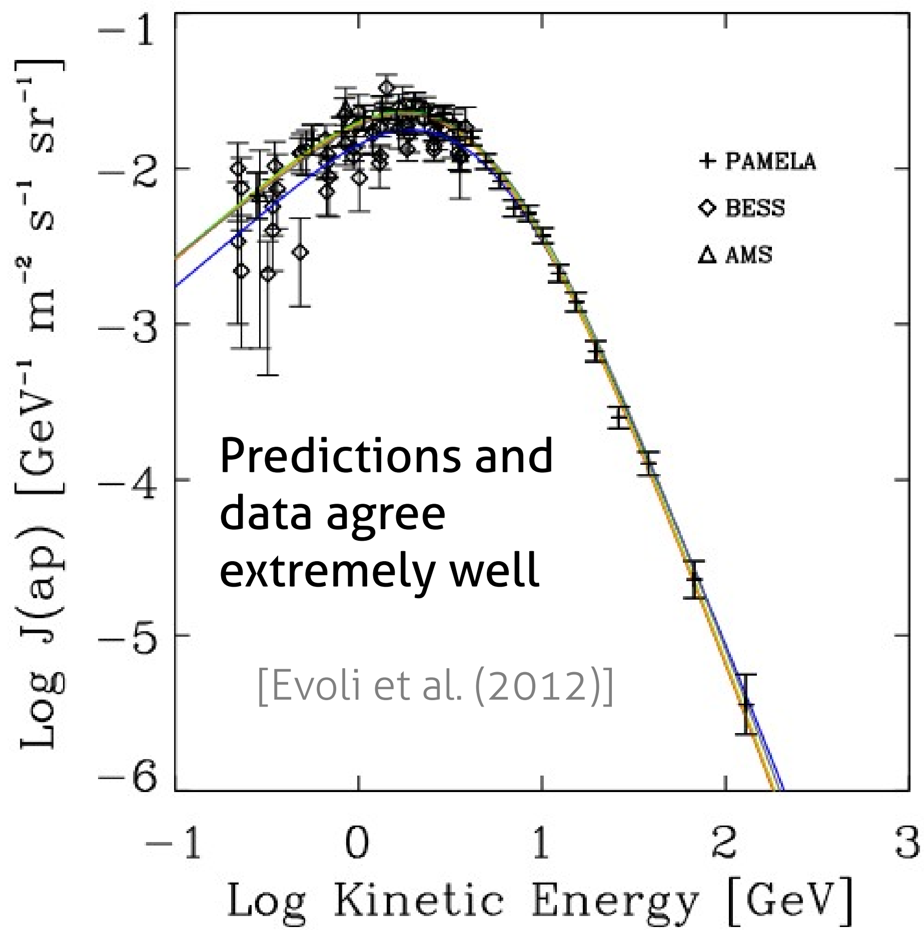
Secondary antiprotons: $n_{\bar{p}} = n_p \sigma(p \to \bar{p}) \cdot G_{\text{total}} \qquad \Rightarrow n_{\bar{p}}$

Predictions for secondary anti-protons

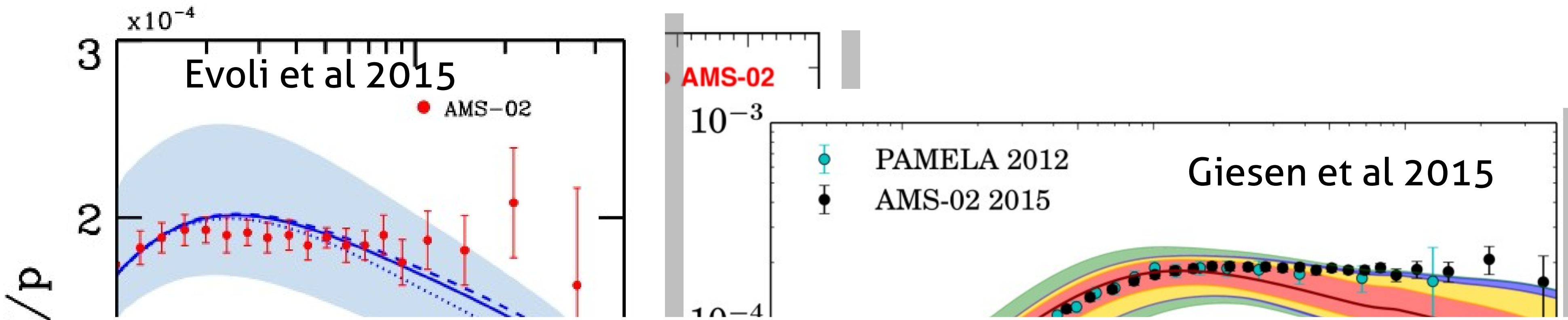
Viable parameters for the propagation model: (fit to B/C and p data)

Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Fig.s
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray



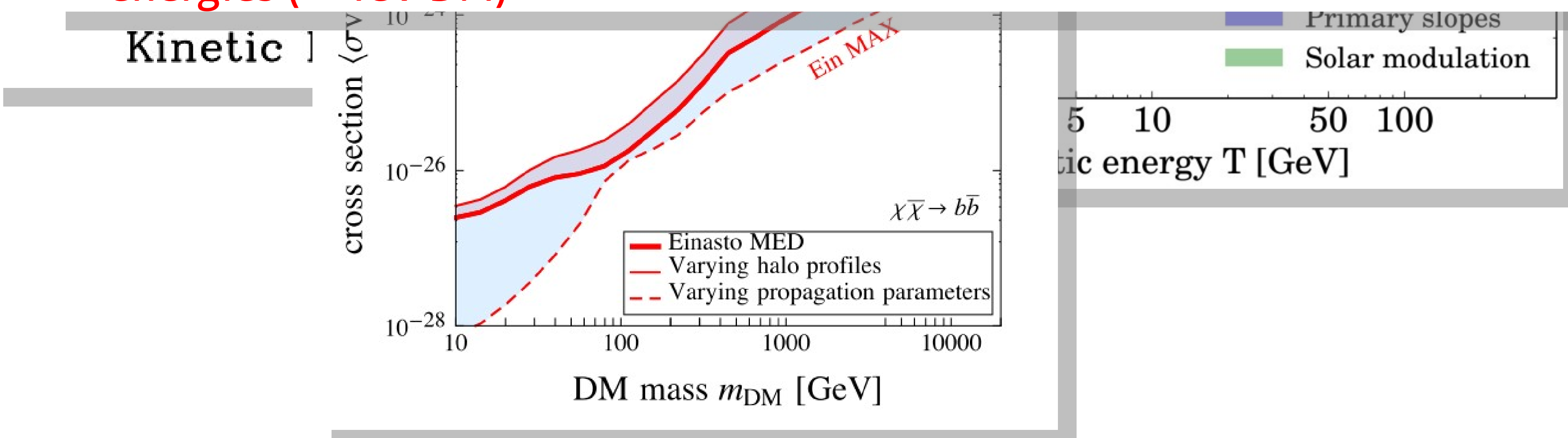


Recent AMS-02 results



Situation:

- No signficiant excess of anti-protons above secondary production
- Future potential:
  - Better understanding of systematics (not easy)
  - Potential for observation of a clear excess with characteristic shape at high energies (→ TeV DM)



Important gamma-ray experiments
GeV to TeV energy range

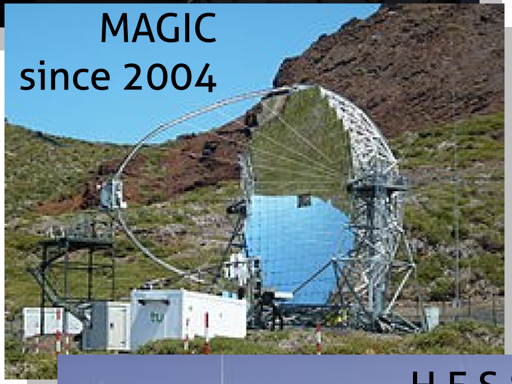
Space based:
(Pair conversion detector)

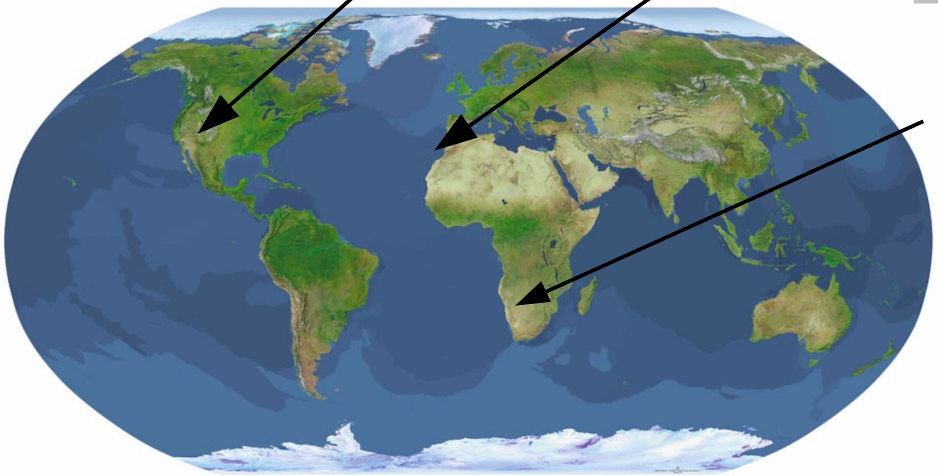
Fermi LAT
since 2008

20 MeV – 300 GeV
Effective area: 1m^2
Obs. time: 10yr

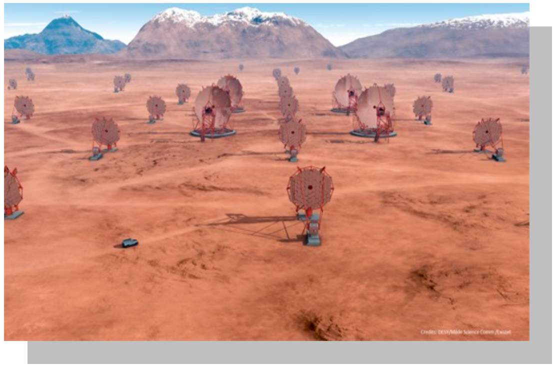
Ground based:
(Atmospheric Cherenkov Telescopes)

10 GeV – 10 TeV
Effective area: 1km^2
Obs. Time: 100h



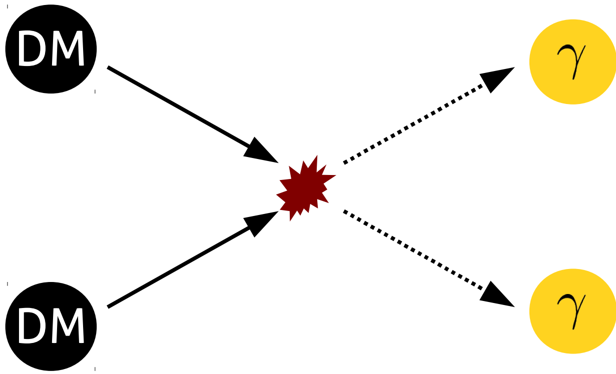


Future: CTA



DM annihilation processes

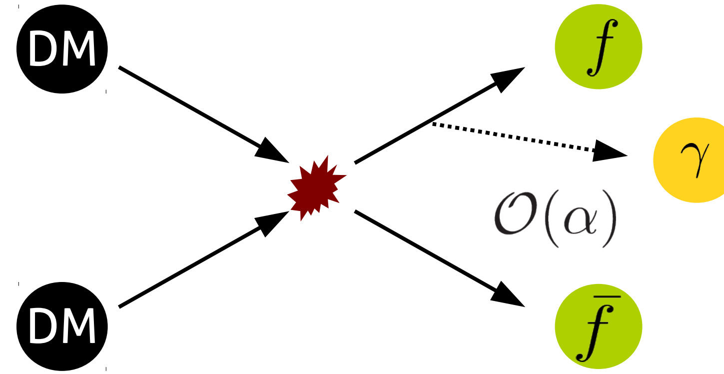
Gamma-ray lines:
Annihilation into photon pairs



[Bergström & Snellman (1988)]

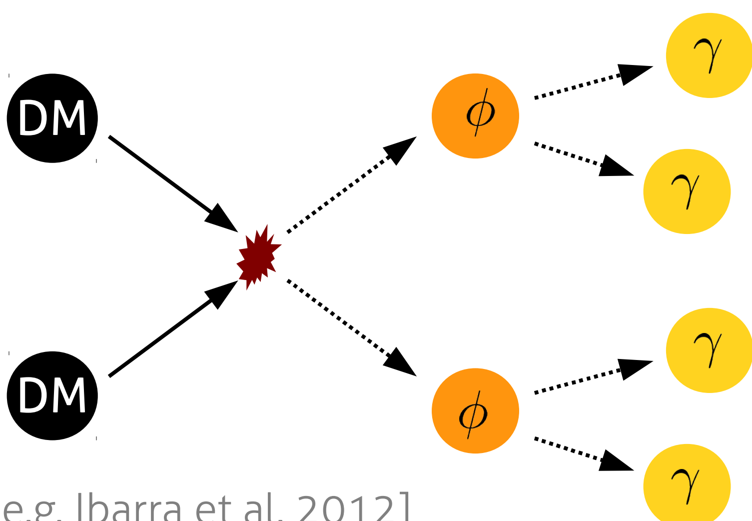
$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$

Bremsstrahlung:
Photons from hard process



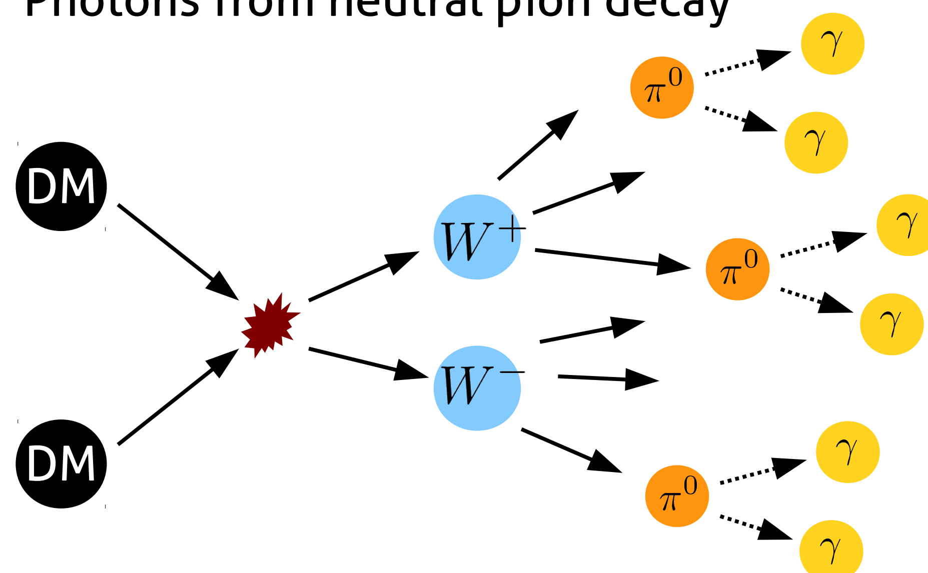
[e.g. Bringmann, Bergström & Edsjö (2008)]

Box-like spectra:
Photons from cascade annihilation

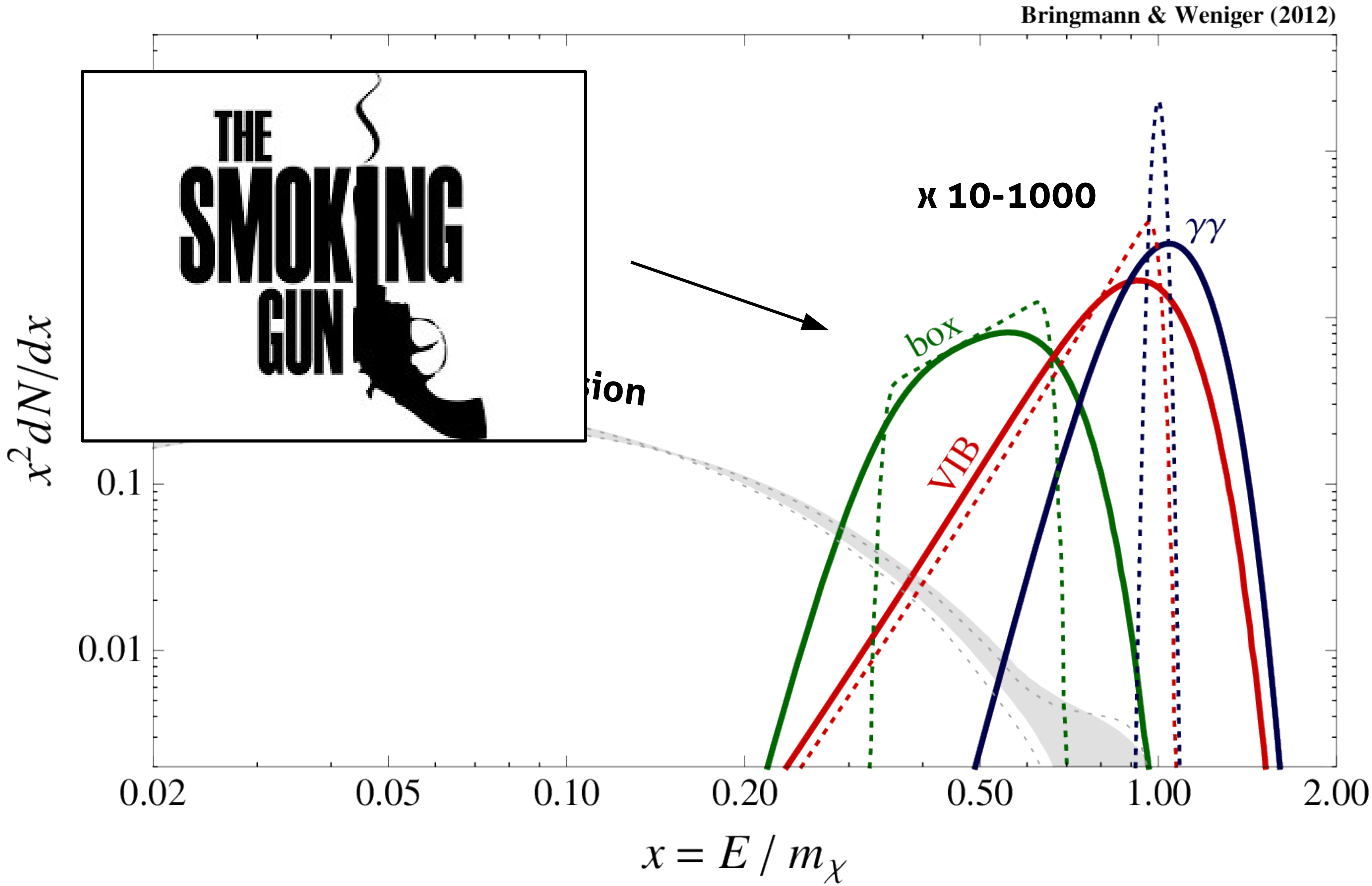


[e.g. Ibarra et al. 2012]

Continuum emission:
Photons from neutral pion decay



Characteristic photon energy spectrum

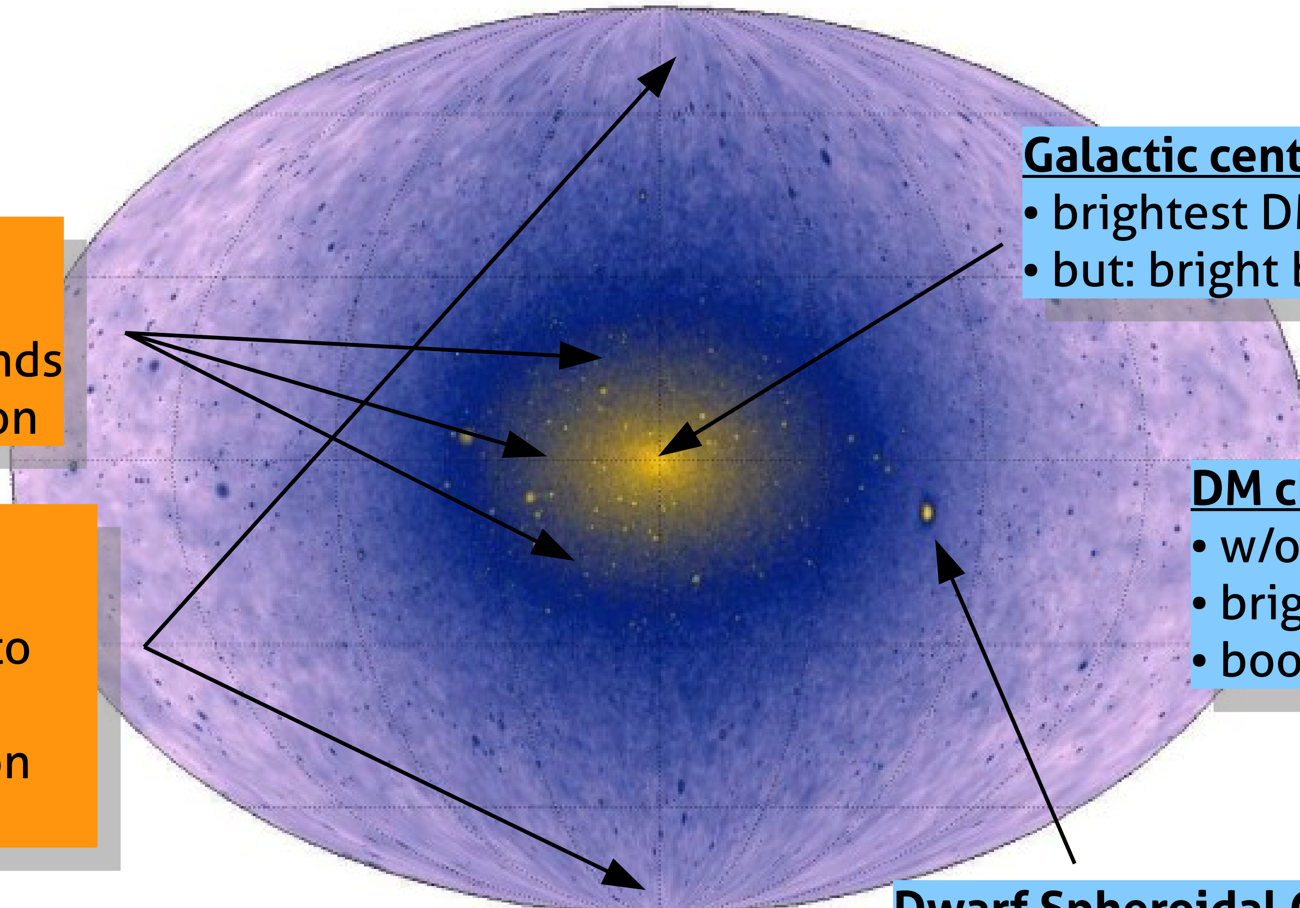


End-point features (x10-1000): Gamma-ray lines, bremsstrahlung, box-like spectra

Many potential targets

Signal is approximately proportional to column square density of DM

$$\frac{d^2\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

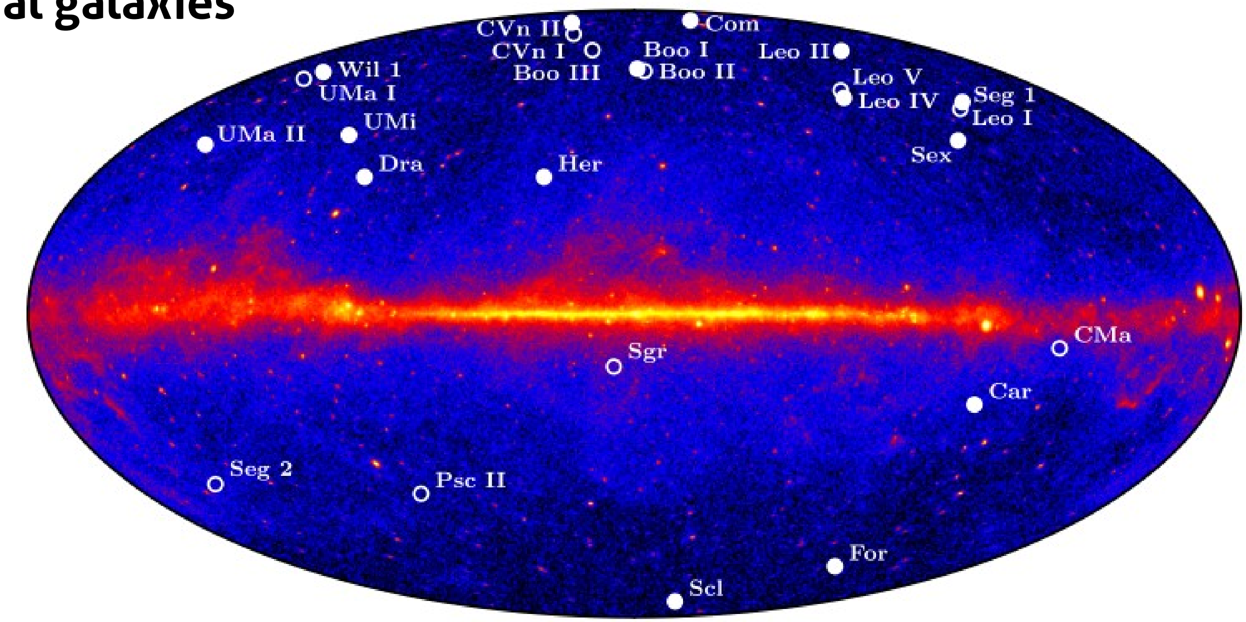
Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

Robust upper limits from dwarf spheroidals

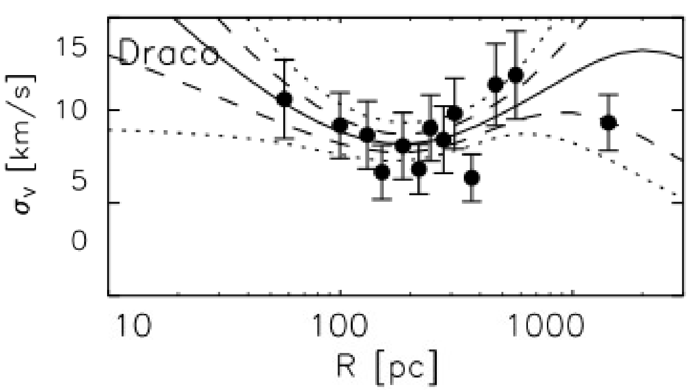
"Stacking" 15 dwarf spheroidal galaxies

- Dark matter dominated
- Nearby and massive
- Background free



(stacked dwarfs)

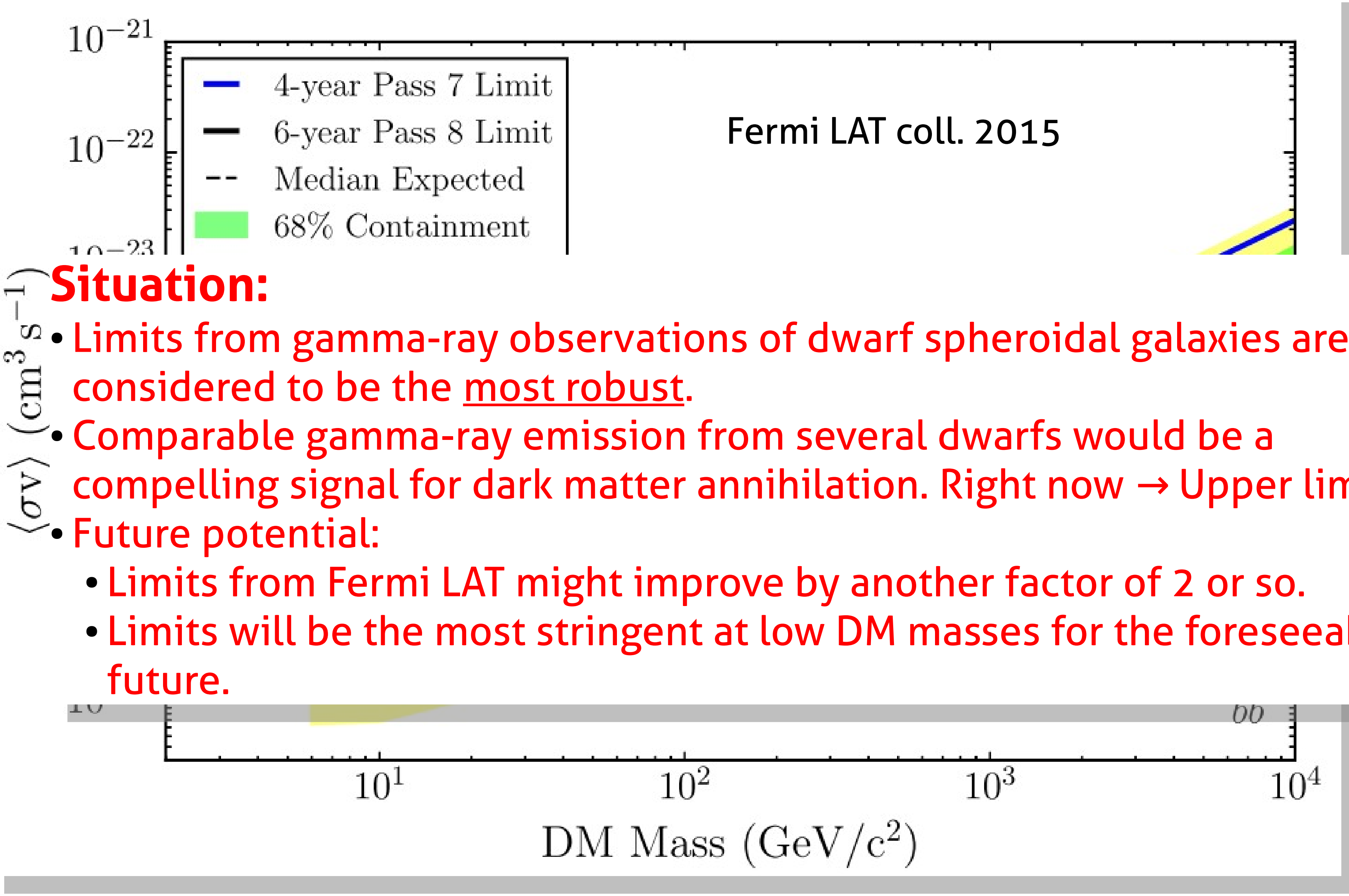
Draco dwarf spheroidal



[Geringer-Sameth+ 2014]

Robust upper limits from dwarf spheroidals

$$\chi\chi \rightarrow \bar{b}b$$



Situation:

- Limits from gamma-ray observations of dwarf spheroidal galaxies are considered to be the most robust.
- Comparable gamma-ray emission from several dwarfs would be a compelling signal for dark matter annihilation. Right now → Upper limits.
- Future potential:
  - Limits from Fermi LAT might improve by another factor of 2 or so.
  - Limits will be the most stringent at low DM masses for the foreseeable future.

Smoking guns signatures: Gamma-ray lines

Gamma-ray lines

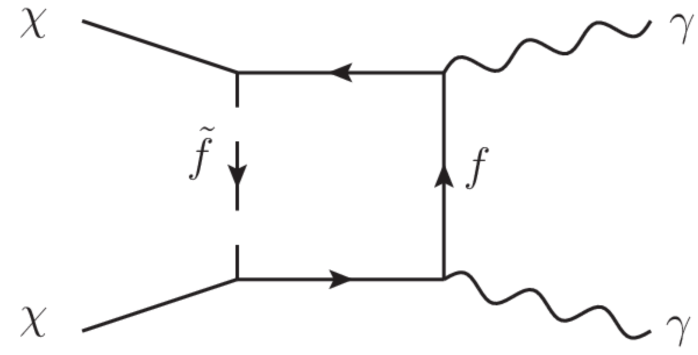
- are produced via two-body annihilation

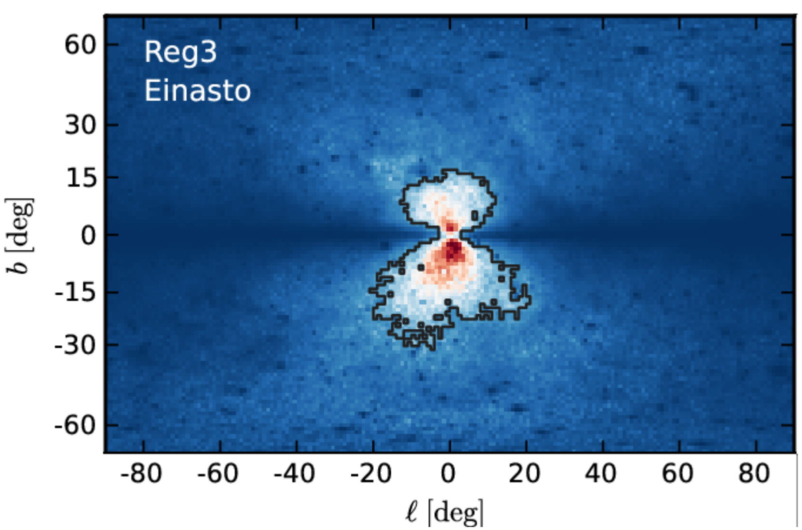
$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$

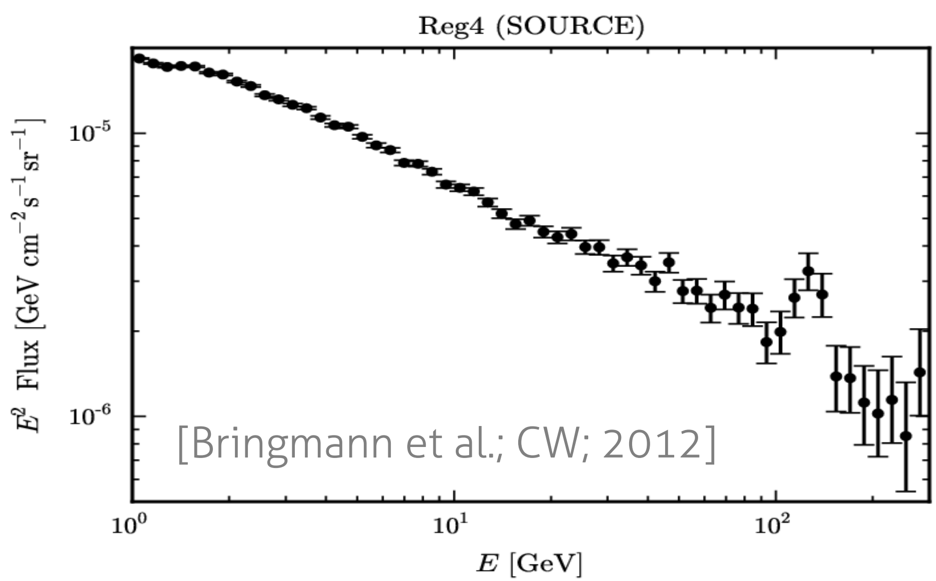
- have a trivial energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

Direct annihilation into photons is loop-suppressed:







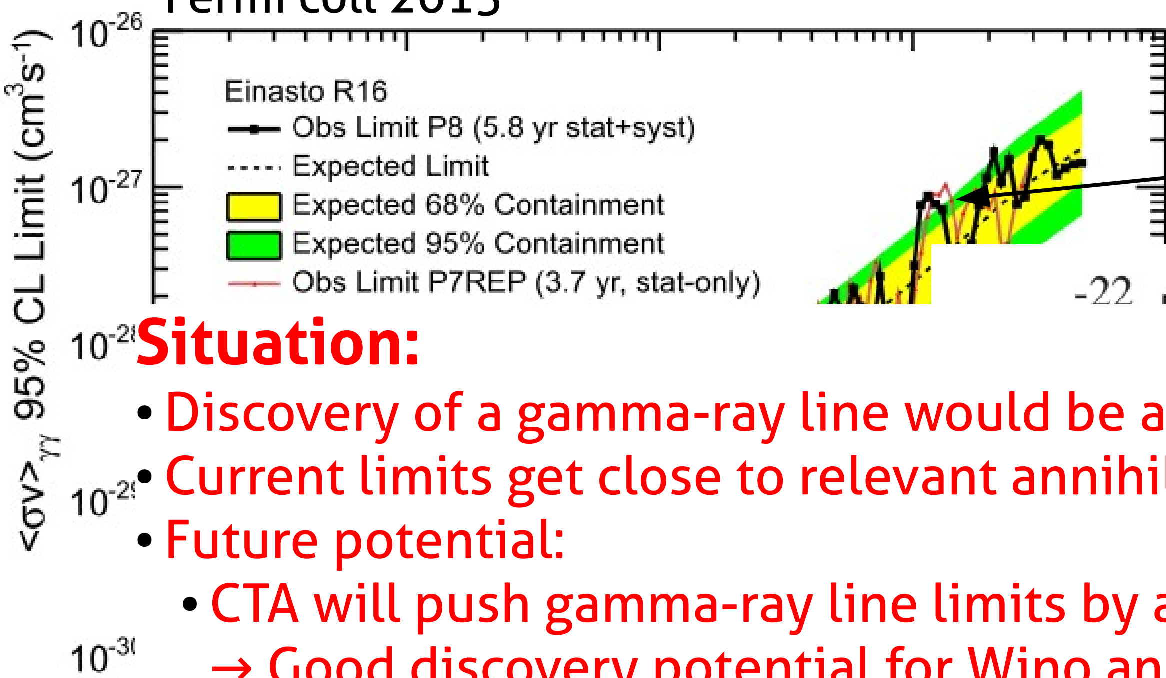
[Bringmann et al.; CW; 2012]

Strong upper limits on annihilation into line photons

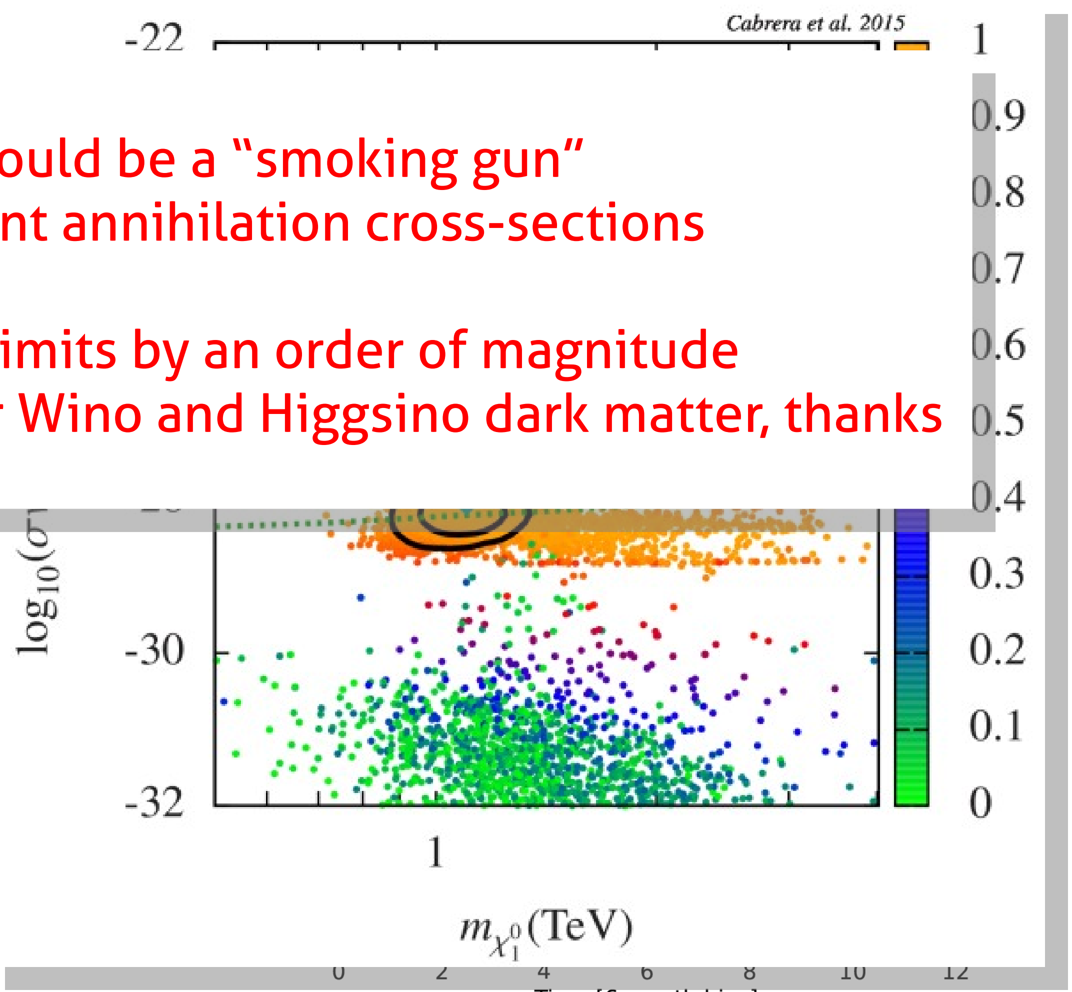
$$\chi\chi \rightarrow \gamma\gamma$$

Fermi coll 2015

“Thermal cross-section”



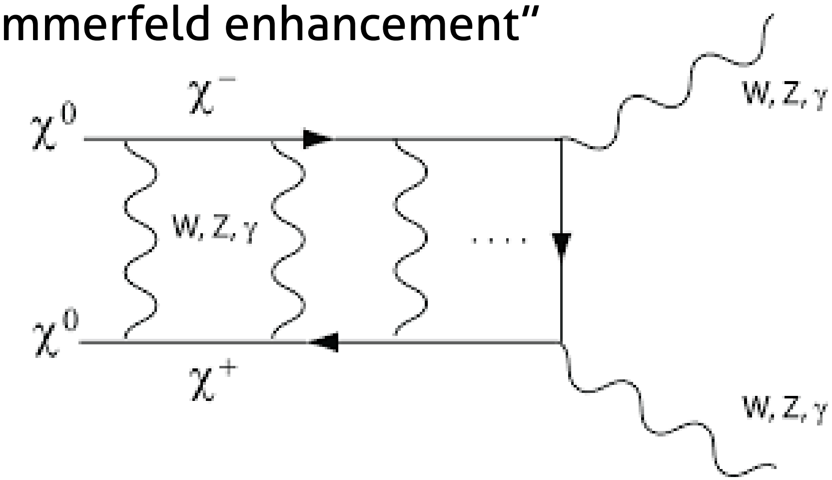
130 GeV feature is gone



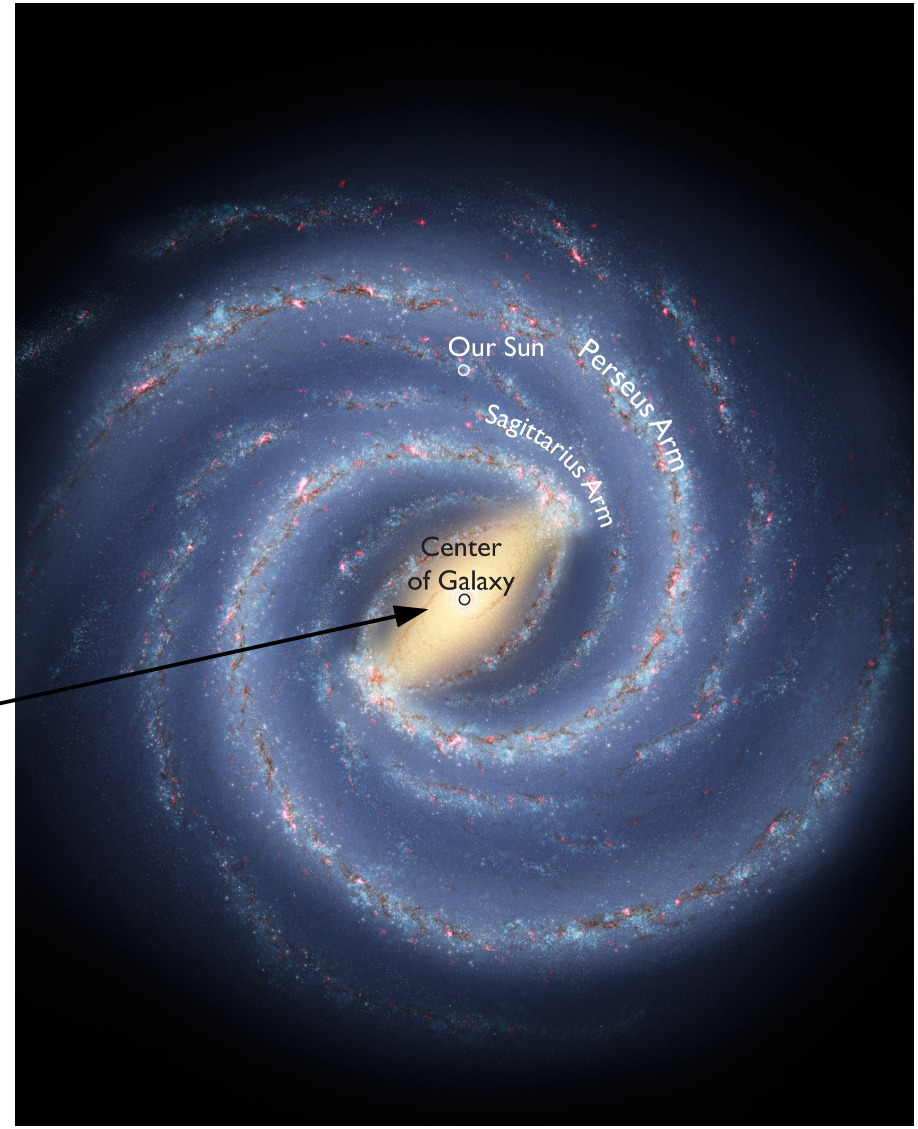
Situation:

- Discovery of a gamma-ray line would be a “smoking gun”
- Current limits get close to relevant annihilation cross-sections
- Future potential:
  - CTA will push gamma-ray line limits by an order of magnitude → Good discovery potential for Wino and Higgsino dark matter, thanks to Sommerfeld enhancement

“Sommerfeld enhancement“



Dark matter searches at the Galactic center



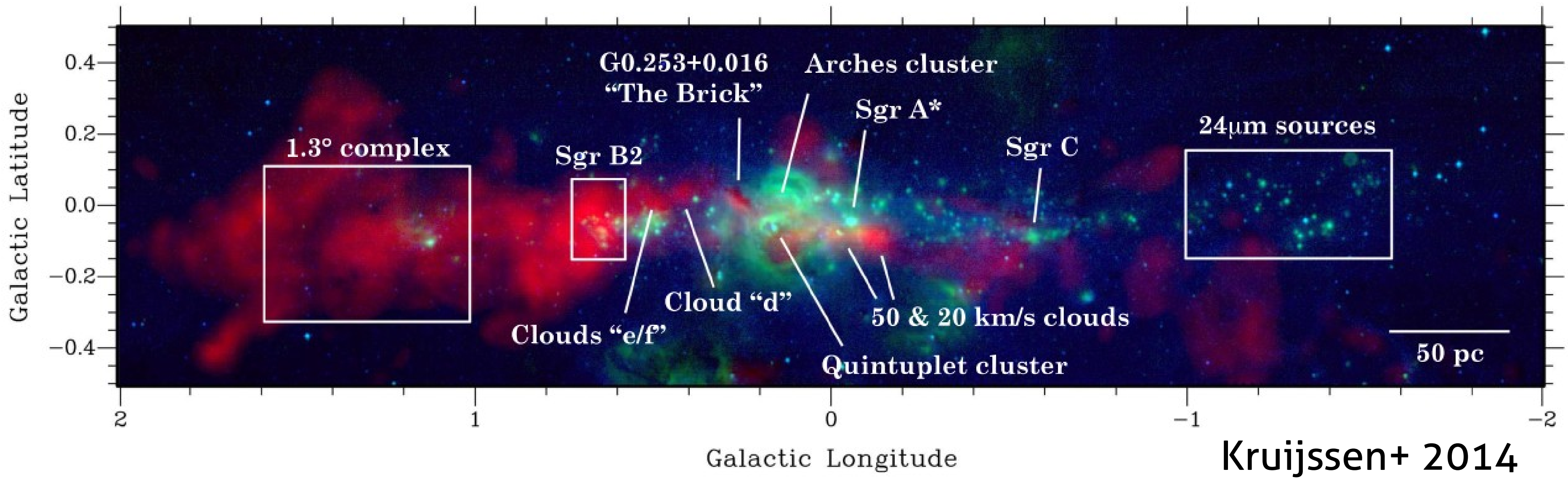
The galactic center:

- Most intense DM signal expected from there
- A singular point in the sky
- Observationally rather challenging
- The “Zone of avoidance”

Still: It is possible to make surprisingly precise statements about the gamma-ray emission from the inner ~2kpc.

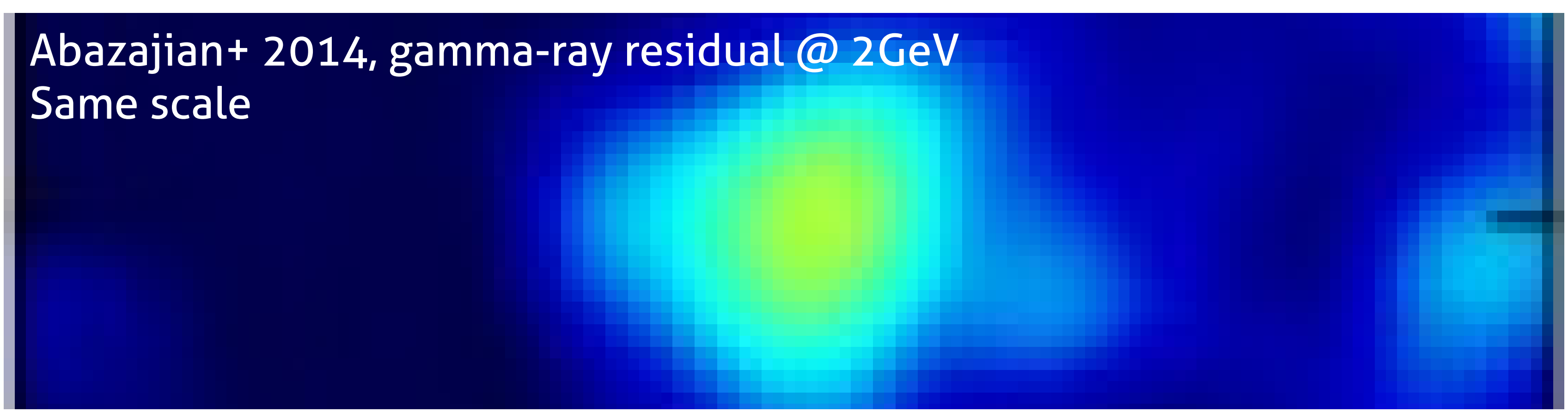
The Galactic Center

- Dominated by central molecular zone (CMZ)
- Contains around ~5-10% of all current star formation and of the molecular gas
- Gas density x100 that of the Galactic disk



Kruijssen+ 2014

Figure 1. Three-colour composite of the CMZ, with in red the HOPS $NH_3(1,1)$ emission (Walsh et al. 2011; Purcell et al. 2012) to indicate the gas with a volume density above a few times 10^3 cm^{-3}, in green the MSX 21.3μm image (Egan et al. 1998; Price et al. 2001), and in blue the MSX 8.28μm image. The MSX data shows PAH emission (mostly tracing cloud edges), young stellar objects, and evolved stars. The labels indicate several key objects and regions.



The "Galactic center excess": First appearance in 2009

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center*

We stu
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Galaxy. W

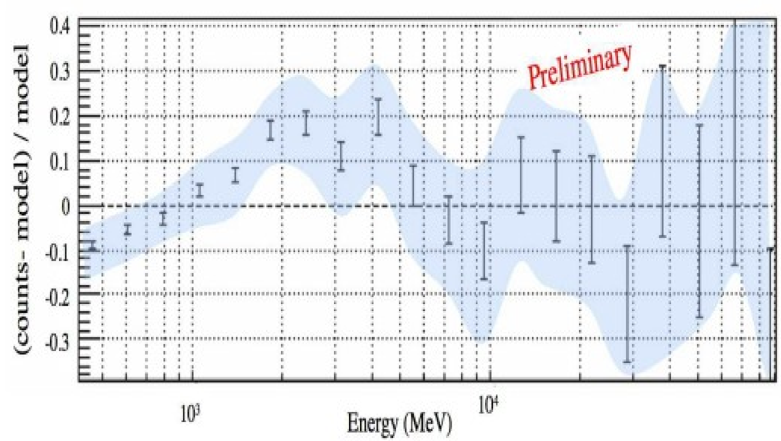
2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

ervations, is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.

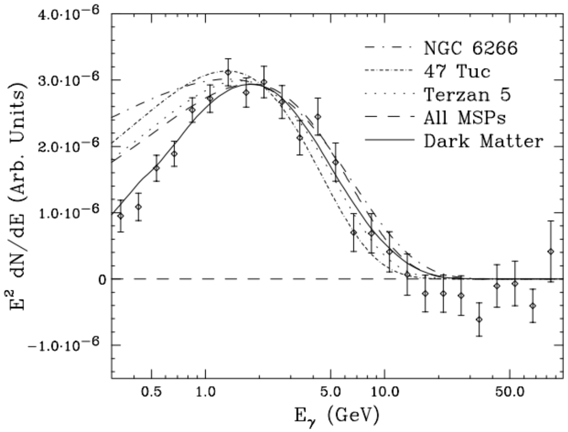
An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.

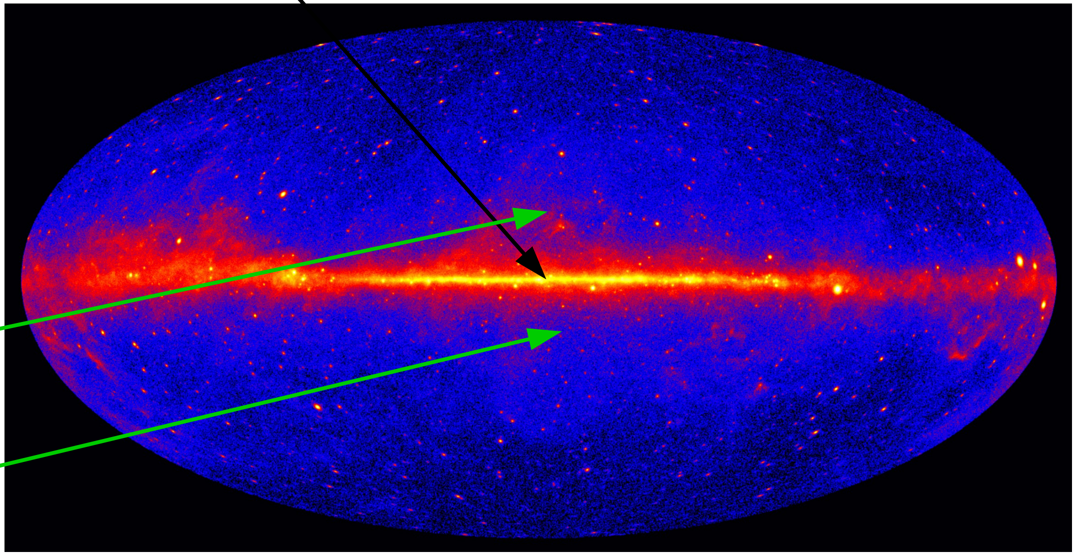


Confirmation in many follow-up studies

Excess at the Galactic center

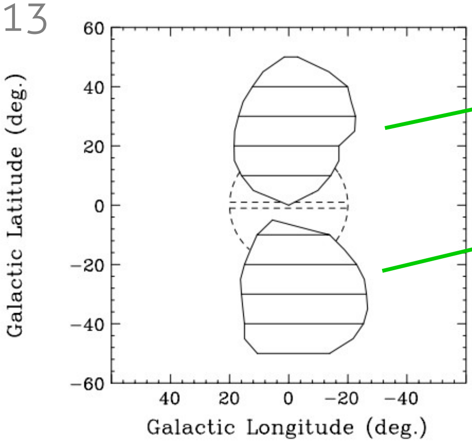
Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+2014





Similar excess at high latitudes
(as expected for an extended DM signal)

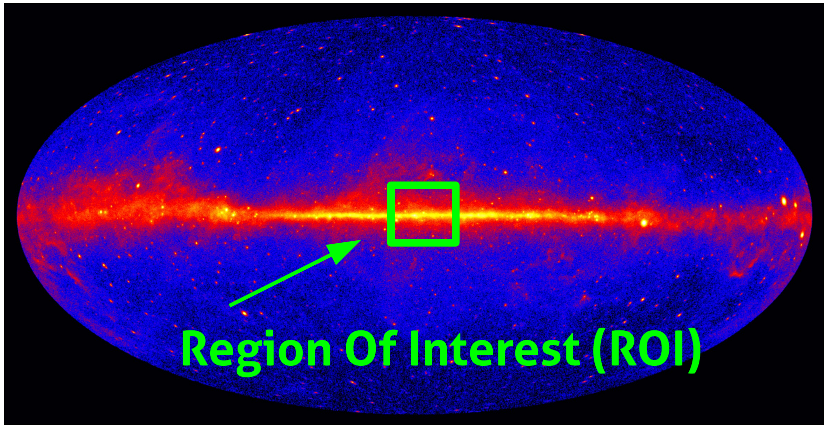
Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014



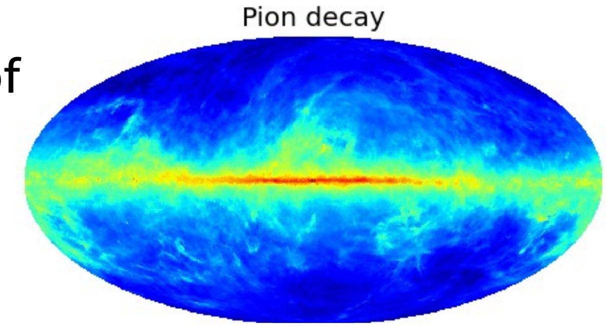
[Hooper & Slatyer 2013]

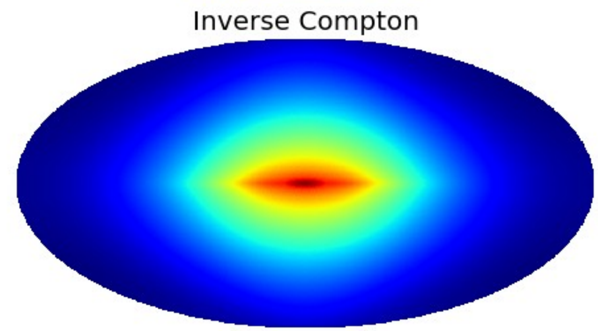
Dark matter searches at the Galactic center

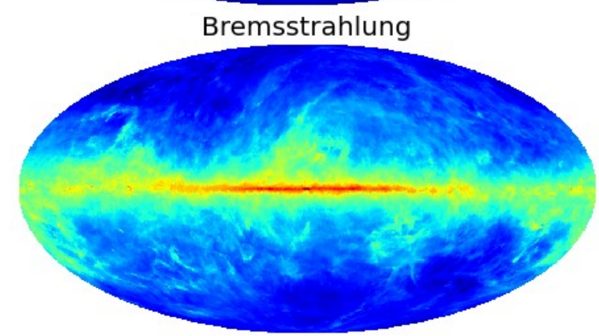
Data (Fermi LAT; > 1 GeV)



Subtraction of astrophysical foreground

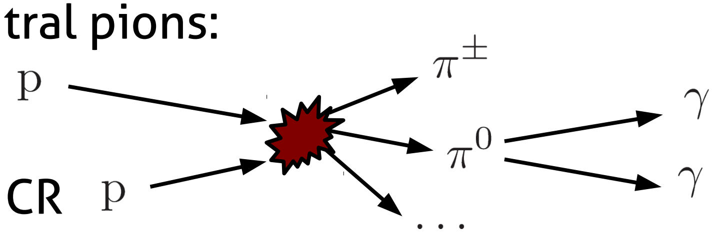




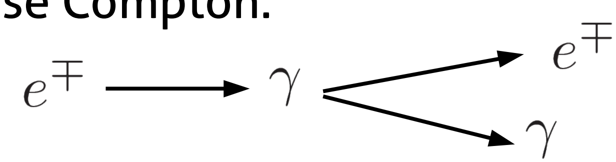


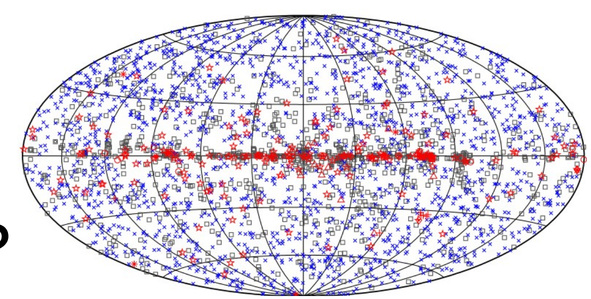
Diffuse emission components

Neutral pions:



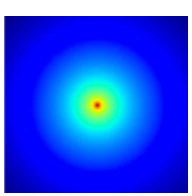
Inverse Compton:





Point sources

?



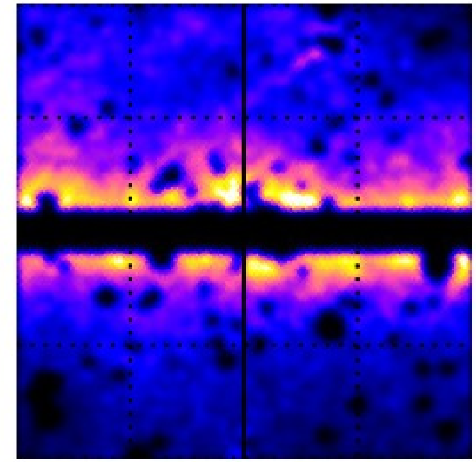
Data – astrophysics:
Do residuals contain something that looks like a dark matter signal?

Analysis of diffuse emission from inner Galaxy

Calore, Cholis, CW 2014

ROI:

- **"Inner Galaxy"**: $2^\circ \leq |b| \leq 20^\circ \quad \text{and} \quad |\ell| \leq 20^\circ$
- We mask all **point sources** from the 2FGL

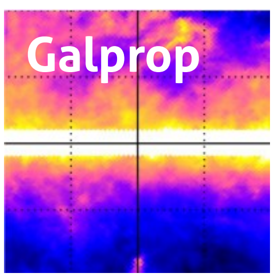


← 40 deg →

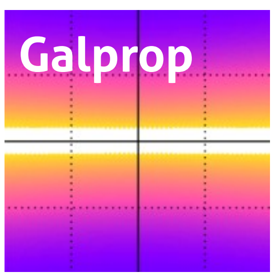
↓ 40 deg ↑

Components in the analysis:

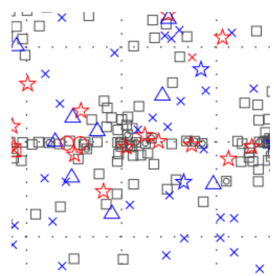
π^0+Bremss free



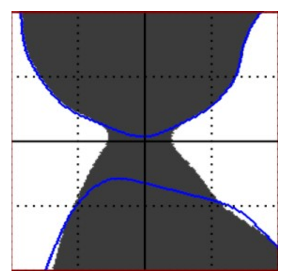
ICS free



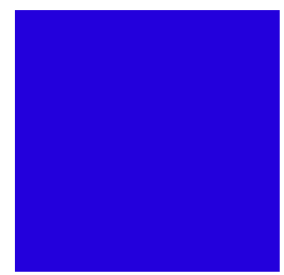
2FGL fixed



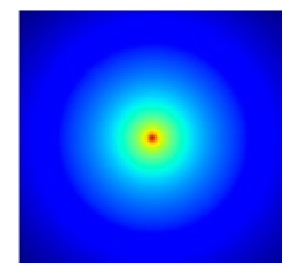
Bubbles constrained



Isotropic constrained



Excess template free

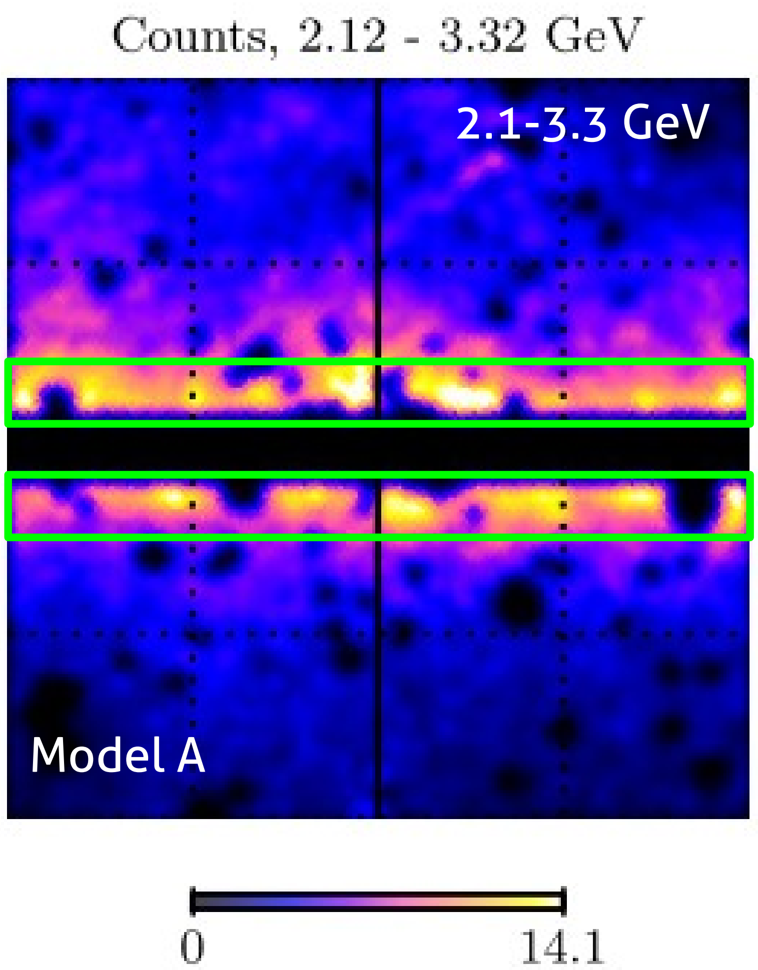


Energy dependent templates

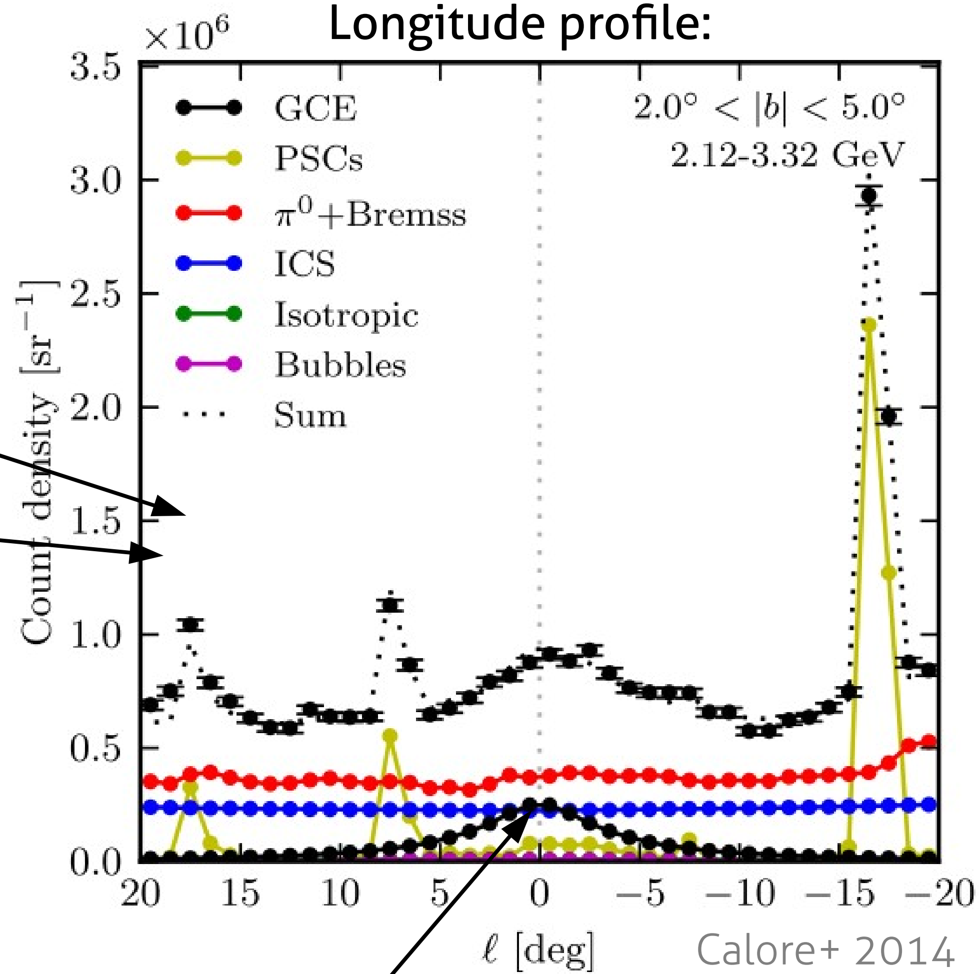
Energy independent templates

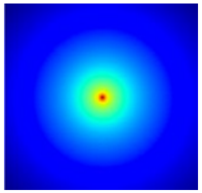
Cosmic-ray propagation and gamma-ray predictions with GALPROP

Results I: Longitudinal variation of excess emission



Longitude profile:

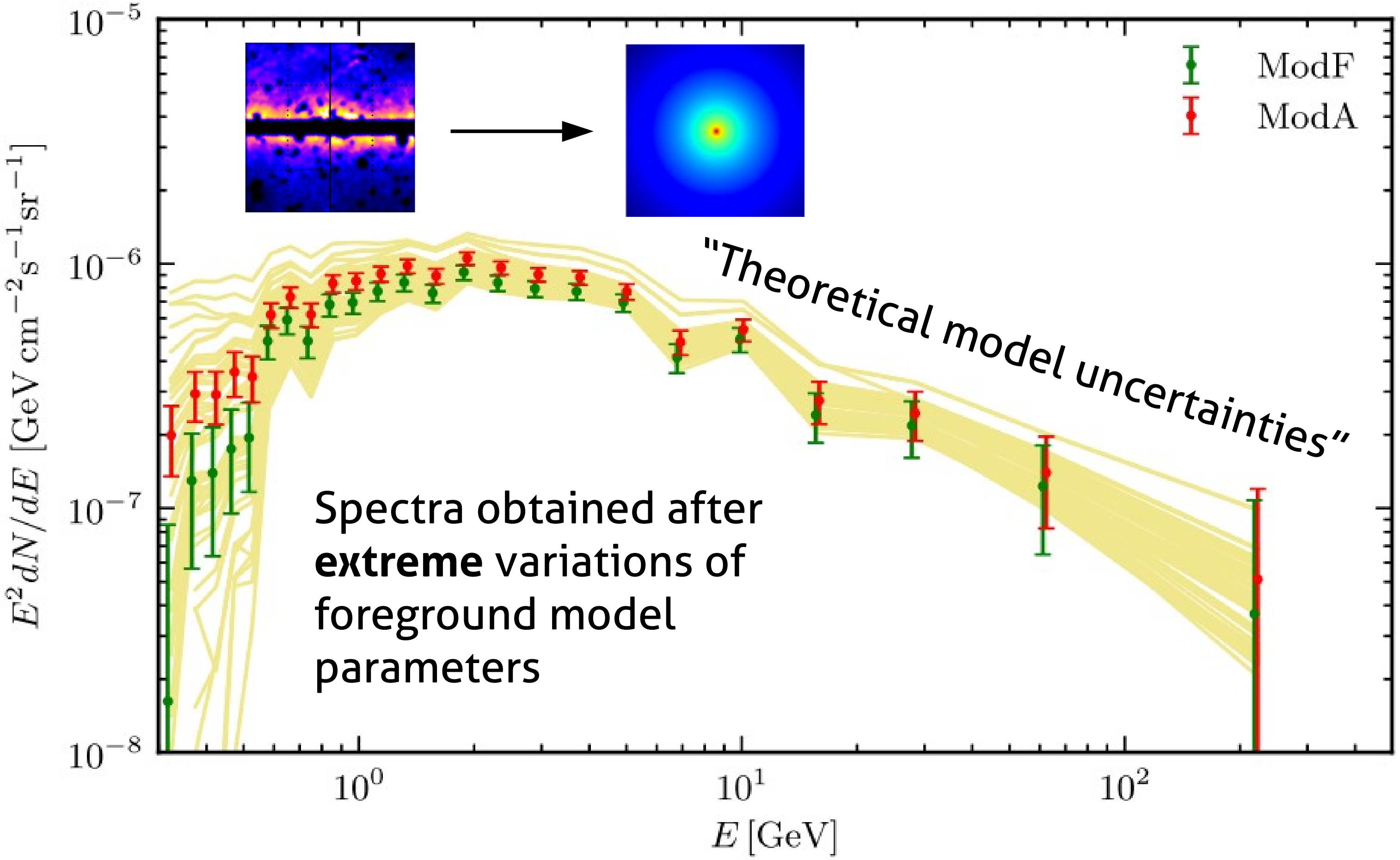




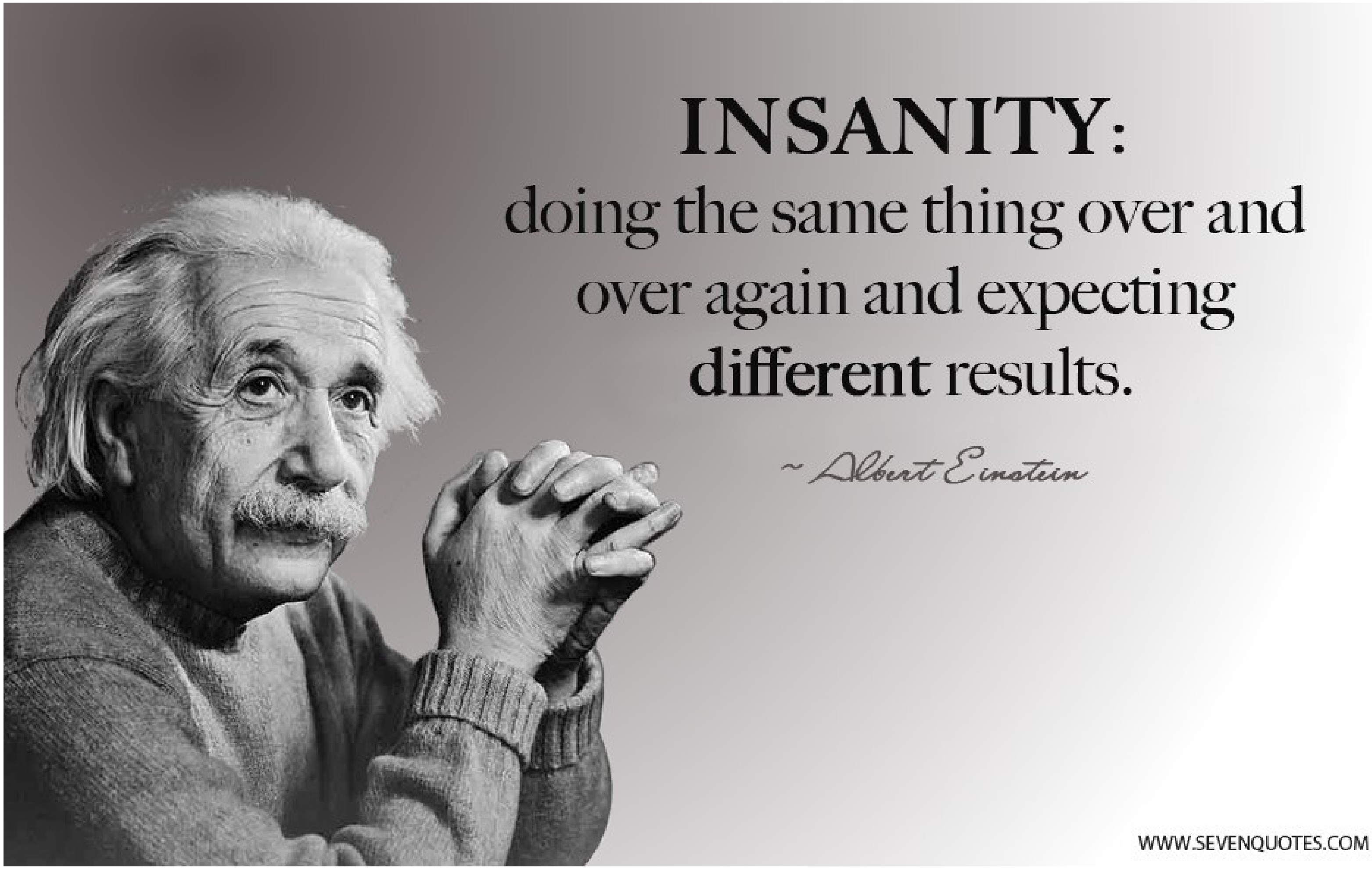
Dark matter like excess emission

Results II: Background modeling uncertainties

For ~60 different models for the Galactic diffuse emission,
with extreme variations of
magnetic field, cosmic-ray propagation, interstellar radiation field, gas maps



In all cases, the excess template spectrum
- rises from 300 MeV to ~1 GeV
- peaks at 1-3 GeV
- falls power-law like above 3 GeV
  (no cutoff at >10 GeV energies as previously claimed)

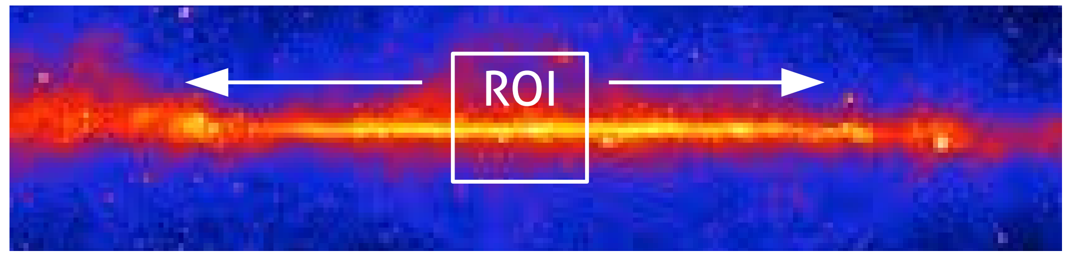


Maybe the 60 background models where not enough...?

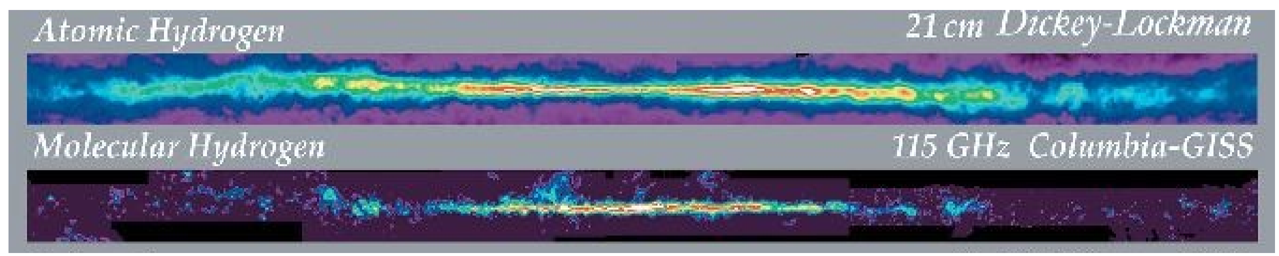
Control regions:
Are there similar excesses in the disk?

We can use Galactic disk as test region to estimate the impact of uncertainties in **gas maps**, modeled **CR distribution**, **point source fits** and masking, and **instrumental effects** on excess template fit at Galactic center.

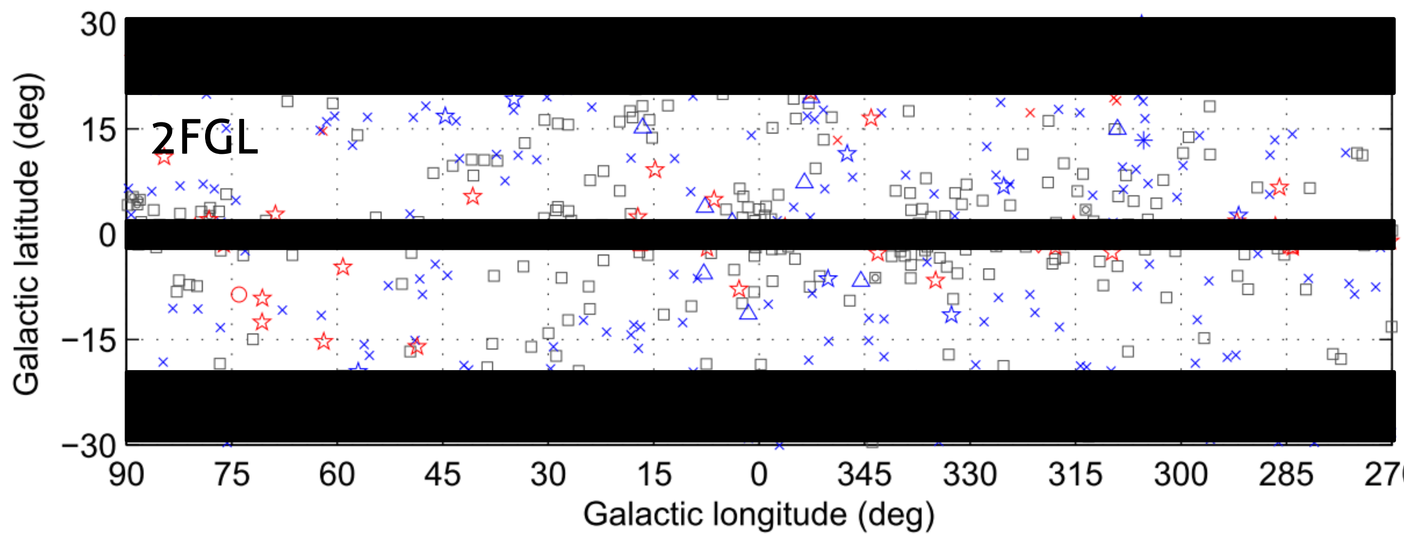
We move the ROI and excess template along disk, and redo our fits.



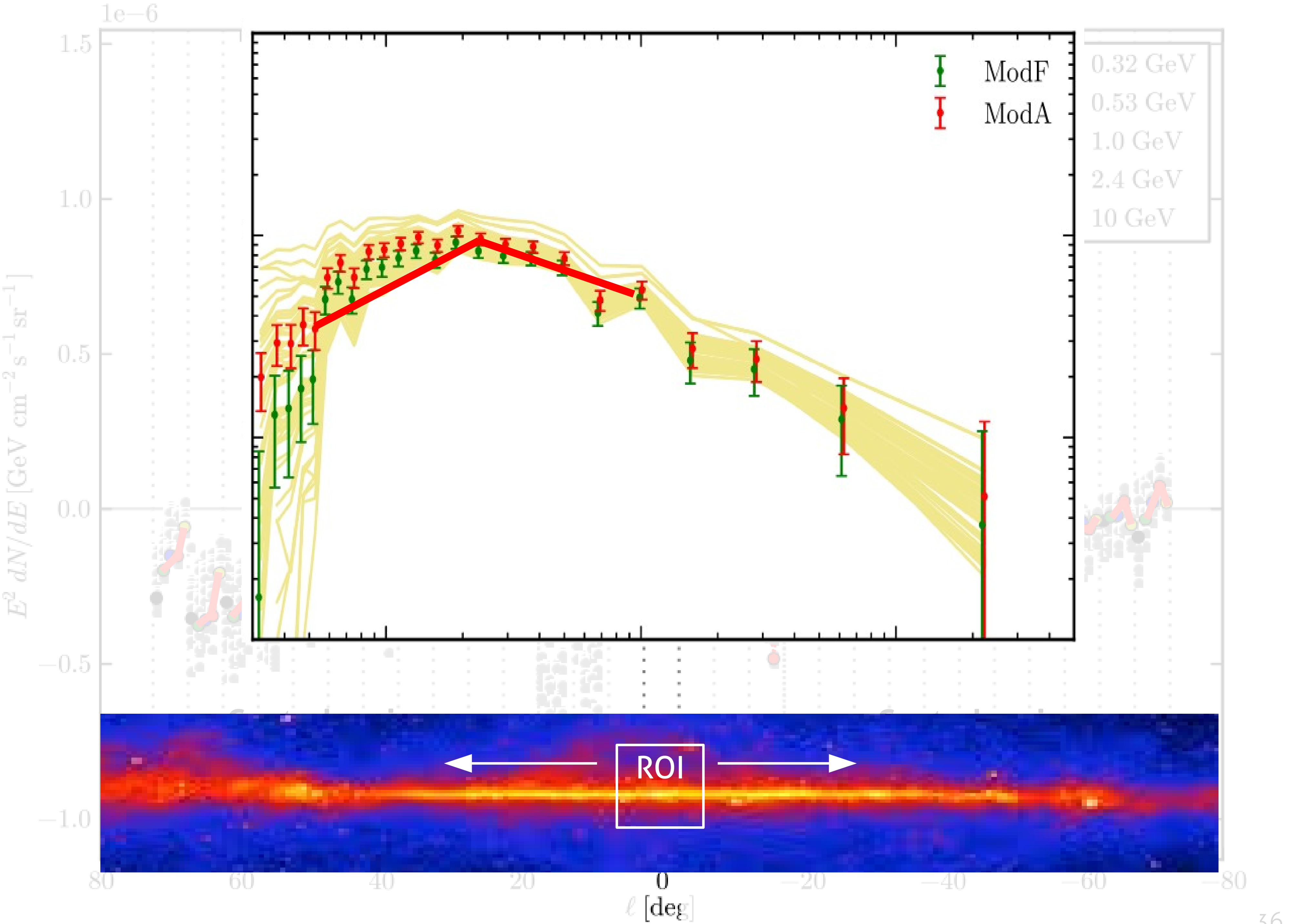
Longitudinal variations photon sources are relatively mild.



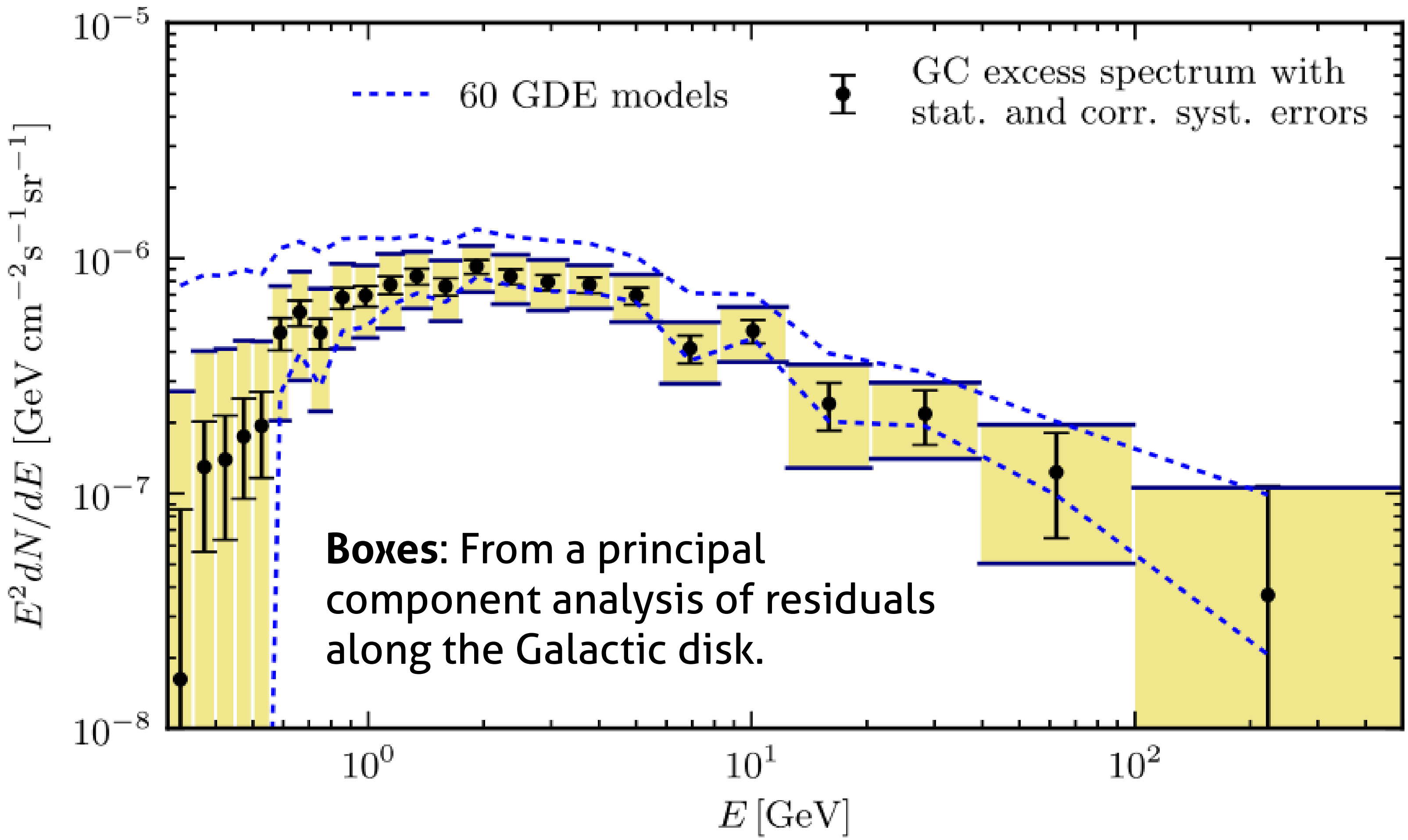
Relevant latitude range



Flux in excess template shifted along the Galactic plane



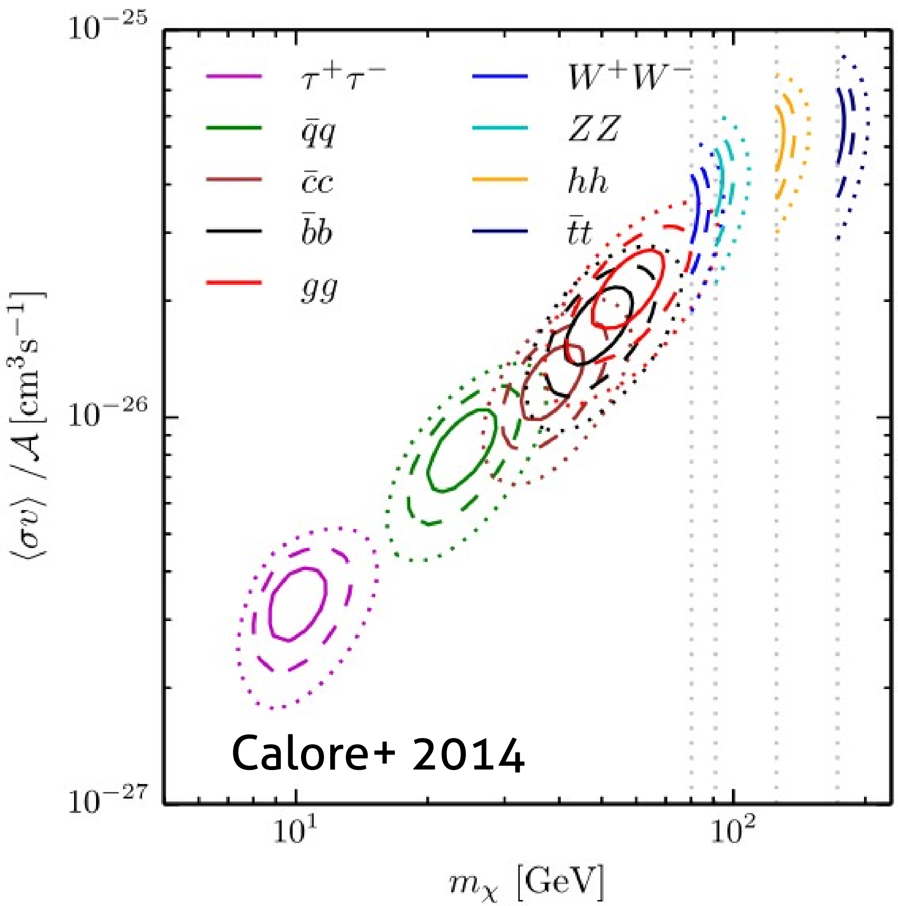
“Empirical” model systematics



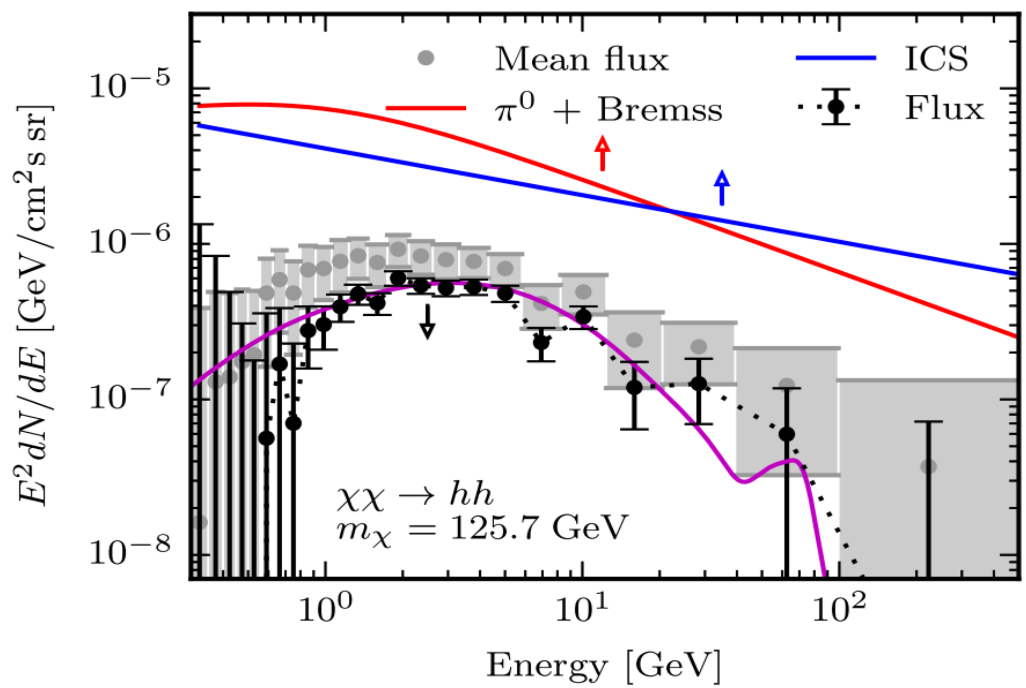
Empirical model uncertainties (yellow) and theoretical model uncertainties (blue lines) are significantly larger than the statistical error over the entire energy range.

Have to take into account systematics to get meaningful results in spectral fits.

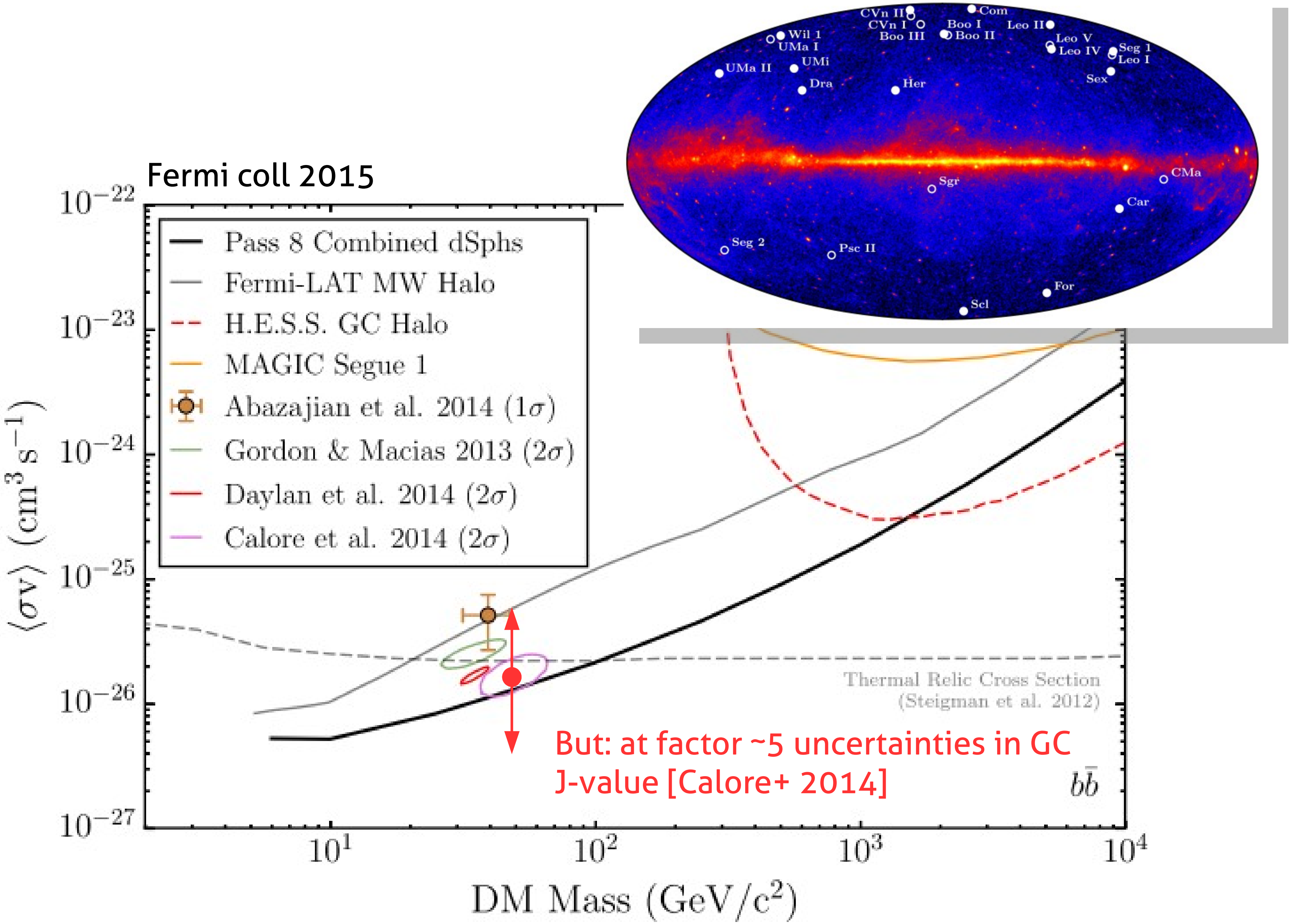
Fits with dark matter annihilation spectra



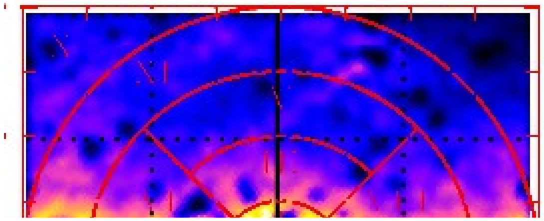
Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
→ $\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
→ hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
[$\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	0.0036]$_{\text{ICS}}$

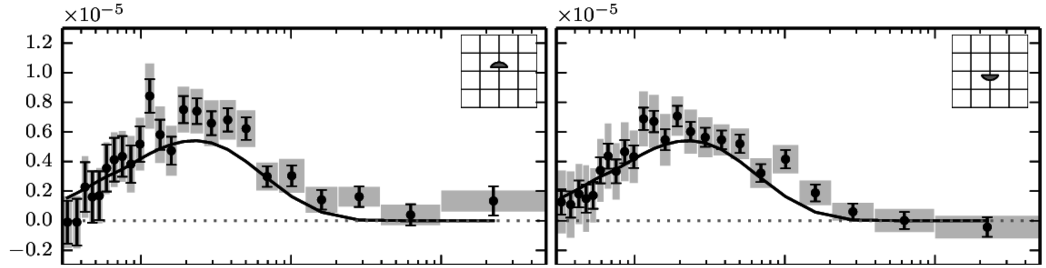


Dwarf limits are in mild tension with GC observations



Dark Matter annihilation works amazingly well



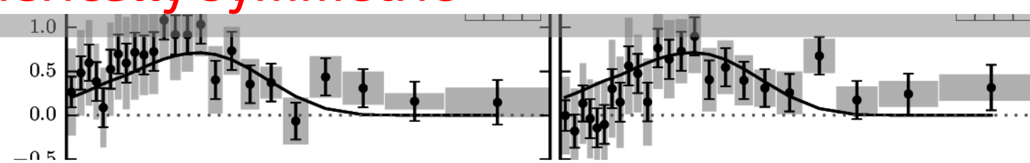


Situation:

- The emission from the inner Galaxy can be described with a surprising accuracy and precision
- It looks very much like the DM signal that we were looking for
  - The spectrum is the same everywhere (always peaks at 2 GeV)
  - The emission is roughly spherically symmetric

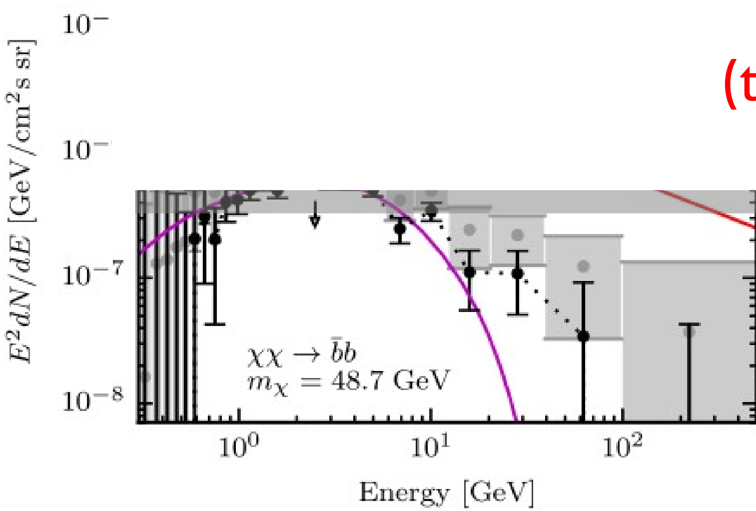
Contracted NFW profile:

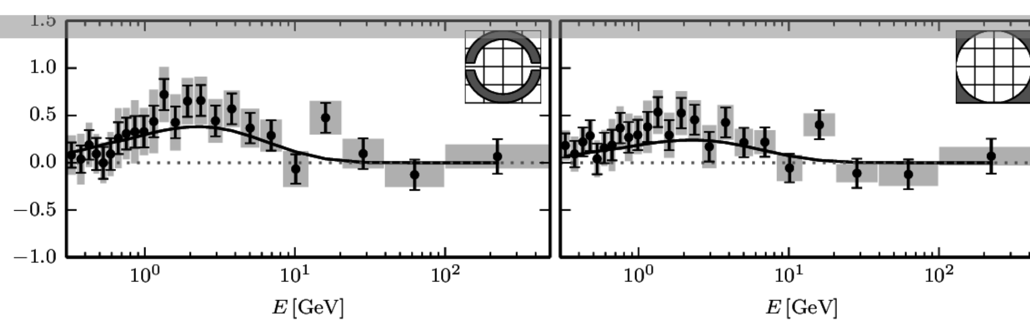
$$\rho_{\mathrm{DM}} = \frac{1}{r^{\gamma}(r_{s} + r)^{2-\gamma}} \qquad \gamma \simeq 1.26$$



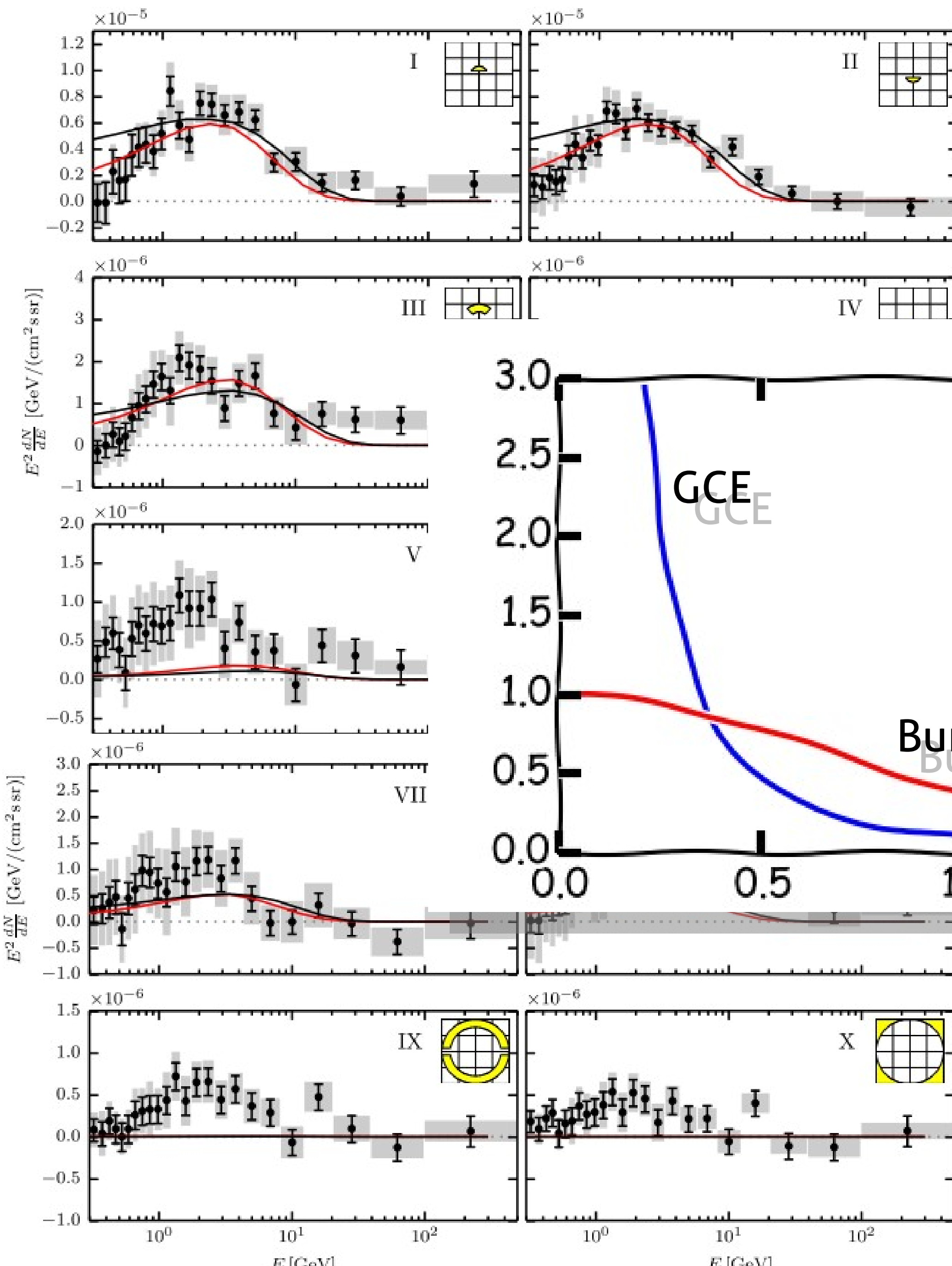
BUT: What about "exotic" astrophysical explanations?

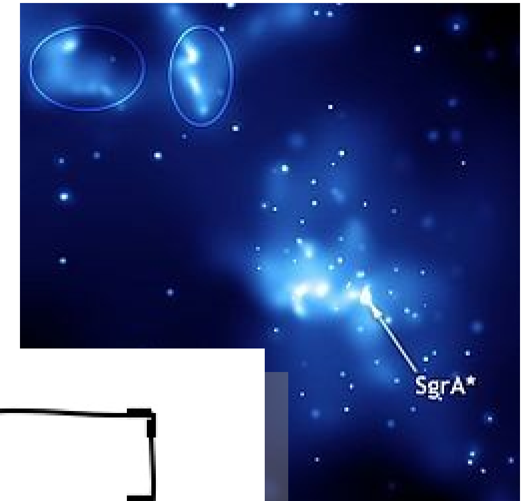
(there is always a but...)

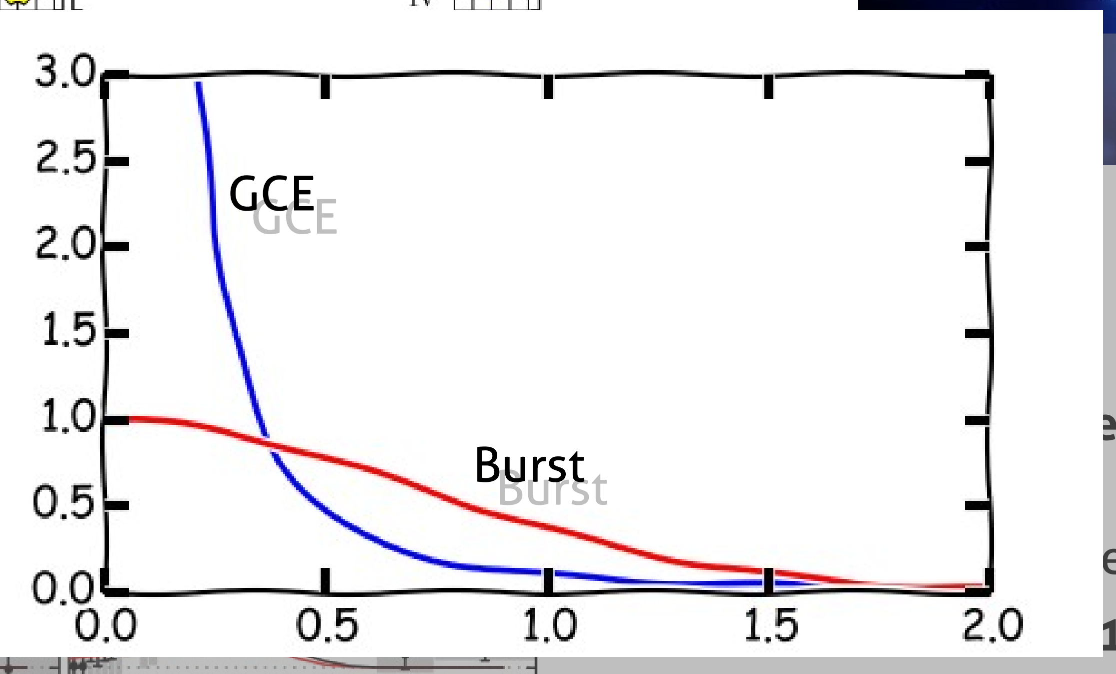




Leptonic outburst at the Galactic center?







...ed to make it work

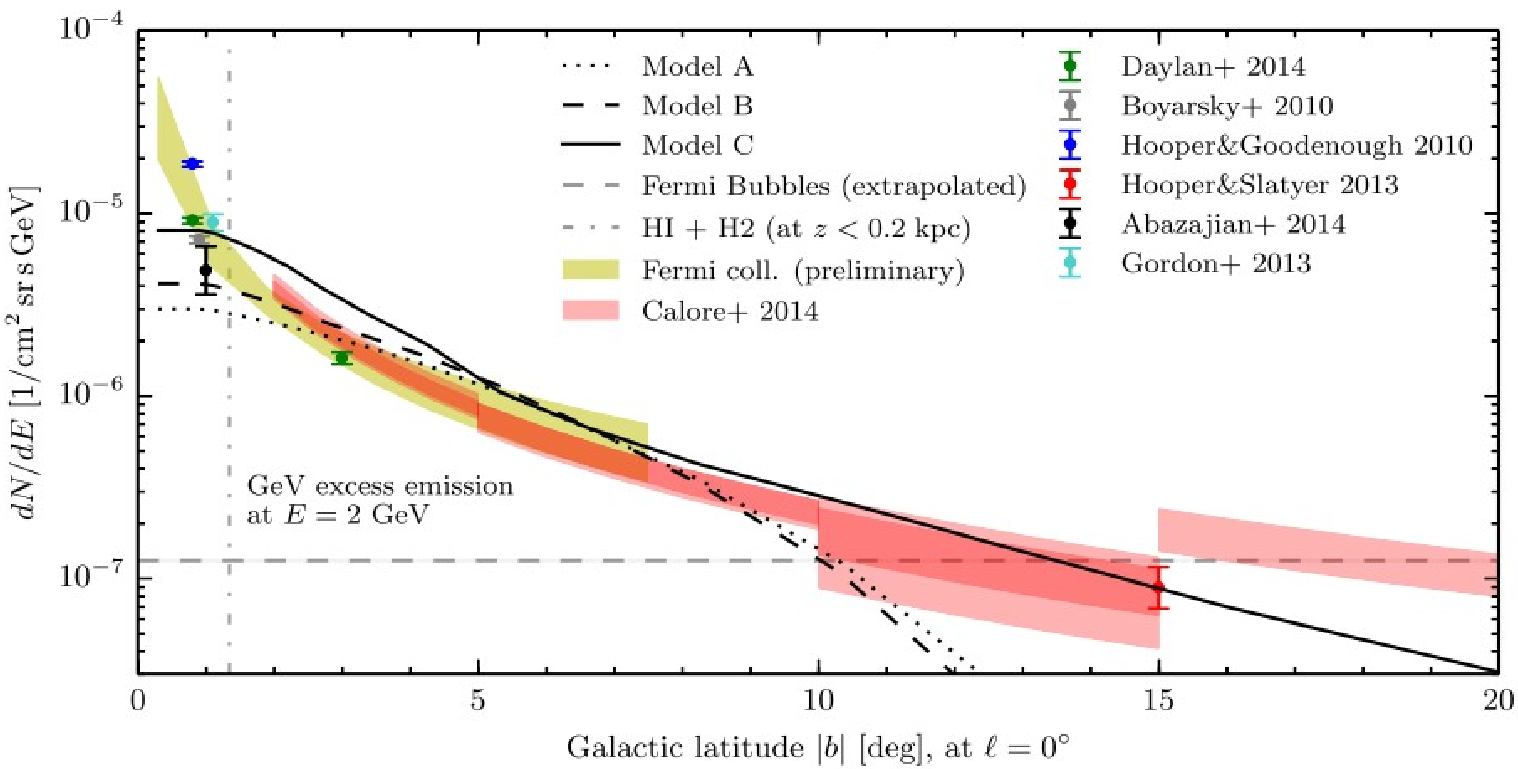
...ection indices (<2)

...1 Myr

- O(1) 10^51 erg injected energy (>1000 SN)
- Still, does not well reproduce the excess at high latitudes

CR propagation with DRAGON [Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Even two bursts cannot explain everything

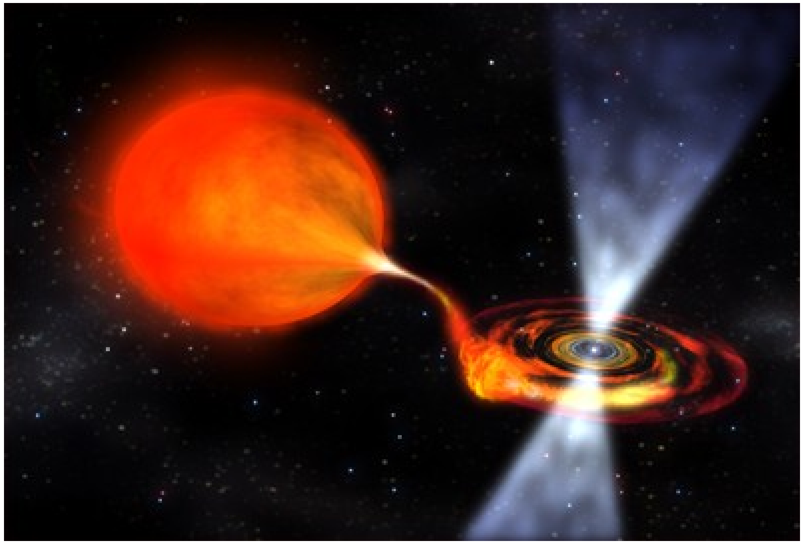


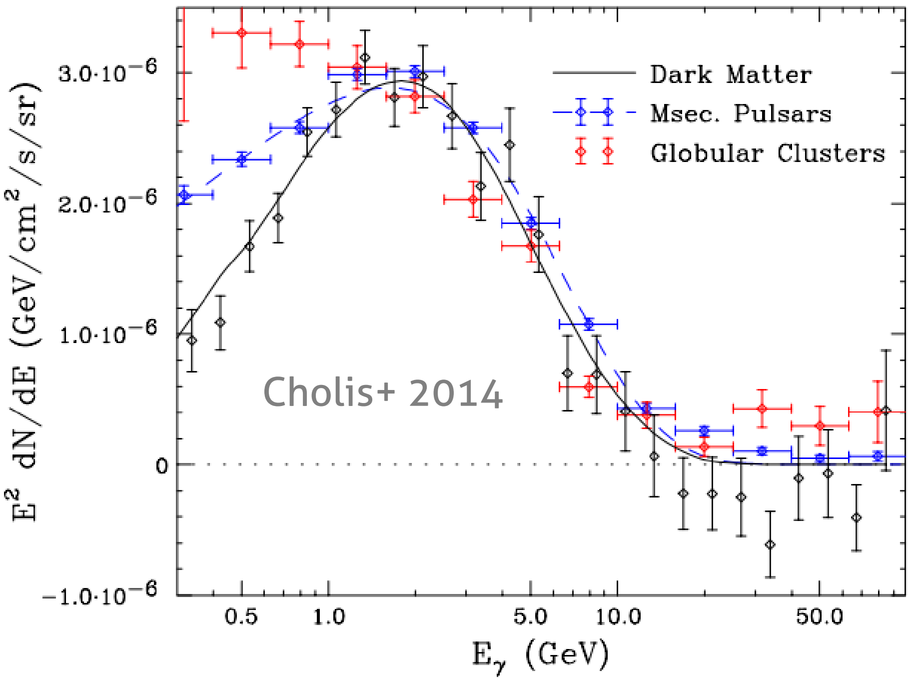
Summary

- It *is* possible to achieve a reasonable description of the data by using two bursts and tuning injection and propagation parameters
- However, the rise of the emission towards the inner few 10 pc is not predicted
- **A series of leptonic bursts are observationally viable, but not likely to explain all of the excess emission**

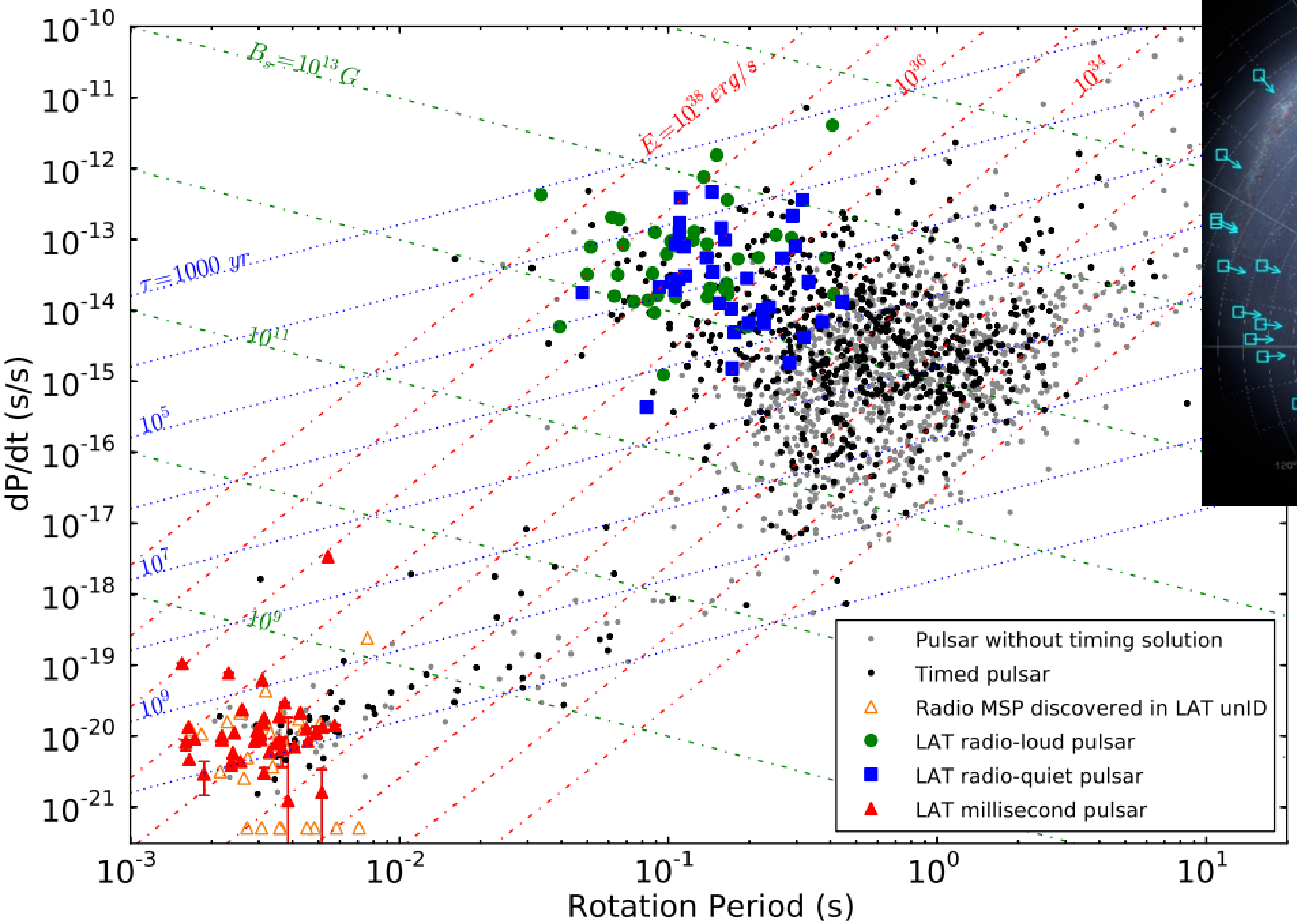
[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

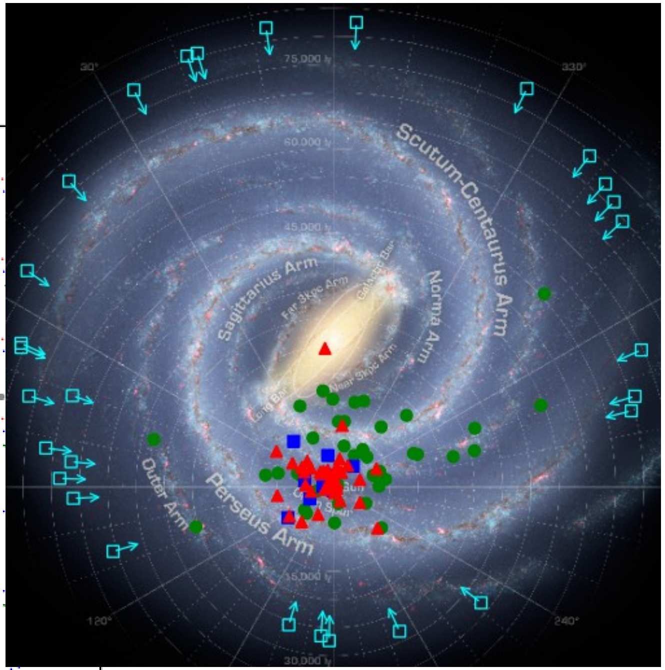
Millisecond pulsars





Gamma-ray detected pulsars





$$B_S = (1.5 I_0 c^3 P \dot{P})^{1/2} / 2\pi R_{NS}^3$$

$$\tau_c = P / 2\dot{P}$$

[Abdo+ 2013, 2nd Fermi Pulsar catalog]

Hypothesis: A population of ~1000 MSPs in the bulge region, with a radial distribution ~r^-2.5`

Effective modeling of MSPs

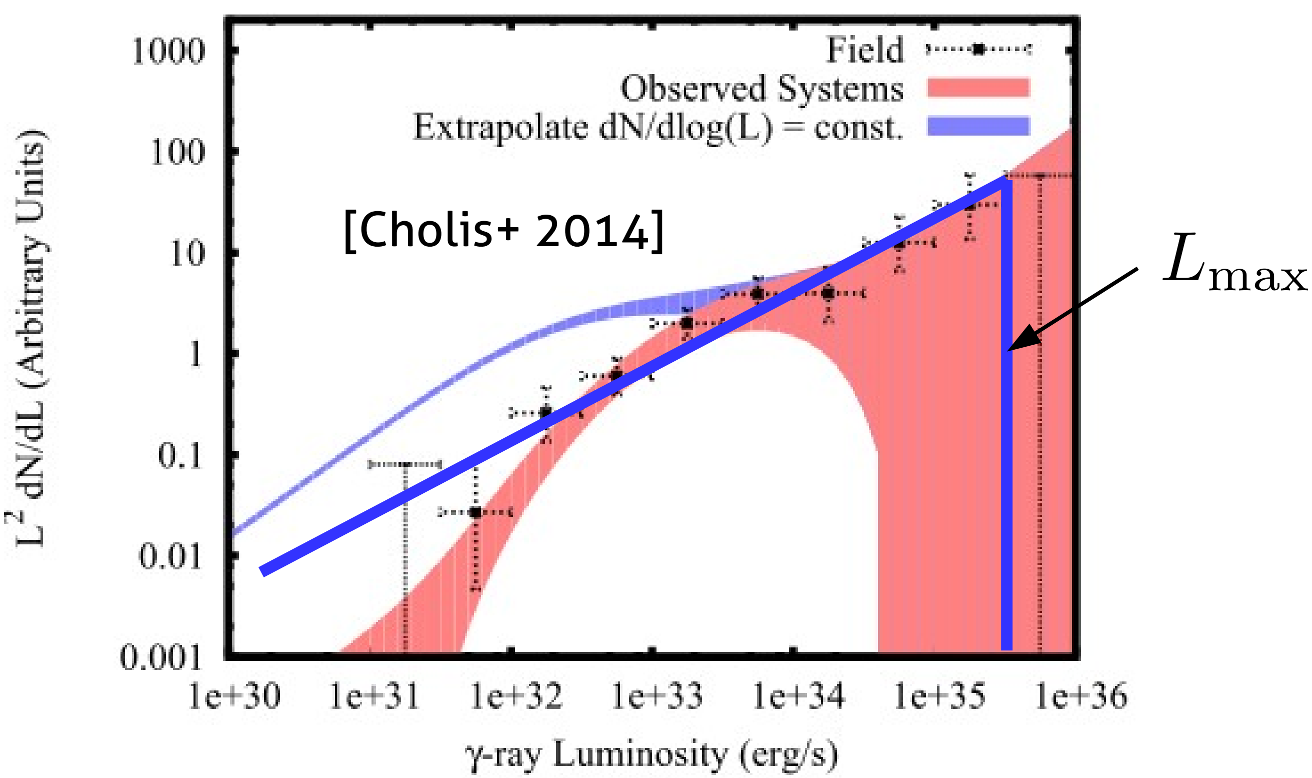
Modeling of unresolved sources

- We assume that they are distributed like required to explain the GCE (with a radial index of -2.5 or so)
- We simulate PSCs that follow a luminosity distribution

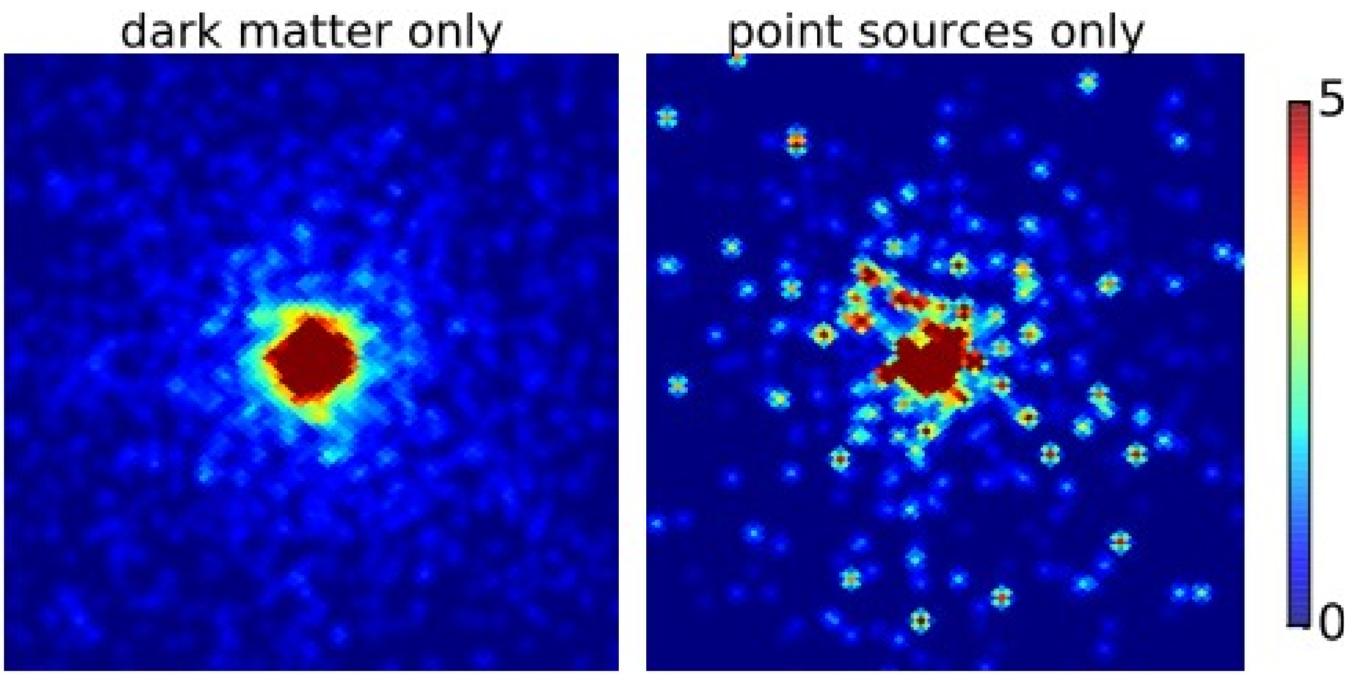
$$\frac{dN}{dL} \sim L^{-1.5}$$

up to some cutoff $L_{\max}$

- Main uncertainties: Slope, normalization and cutoff of the luminosity function. Here: slope fixed to -1.5



Discriminating Millisecond pulsars (MSPs) from DM

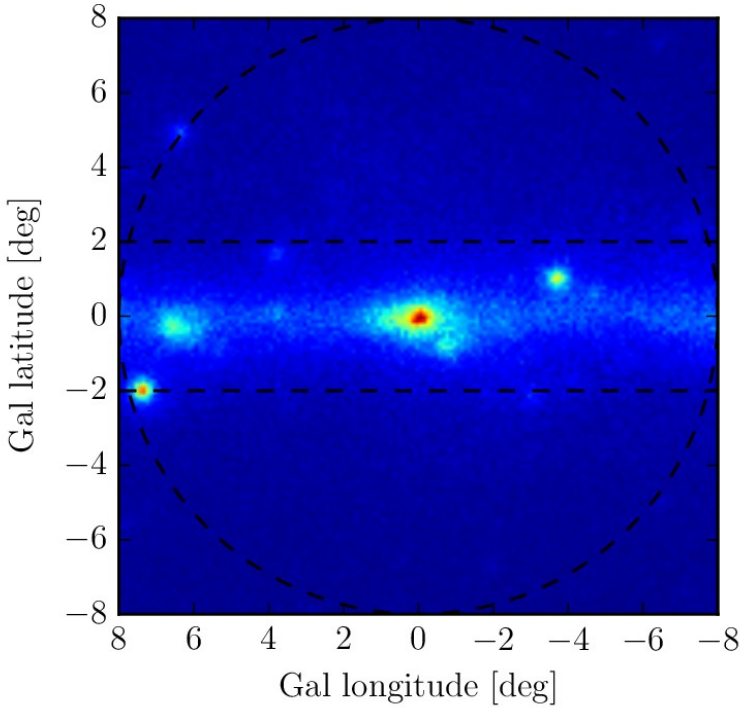


[Lee, Lisanti, Safdi 2014]

MSPs (or other point sources producing the excess) would produce more "speckled" signal than DM.

→ Can be tested with e.g.
• one-point statistics (Lee et al. 2014, **2015**)
• wavelet analysis (next slides)

Wavelet analysis



[Bartels, Krishnamurthy, CW, 2015]

Wavelet analysis in a nutshell:

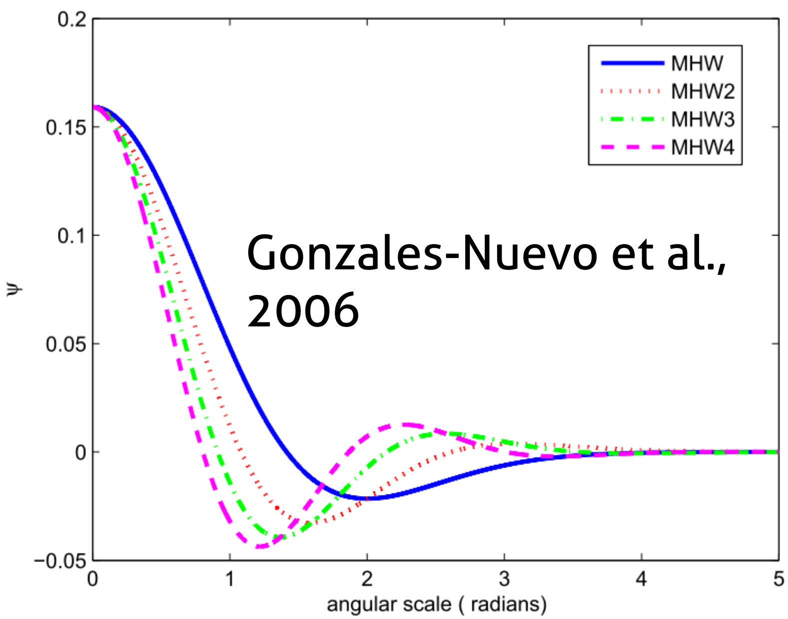
- Remove galactic diffuse emission with wavelet transform

$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega) \equiv \int d\Omega\, \mathcal{W}(\Omega - \Omega')\mathcal{C}(\Omega')$$

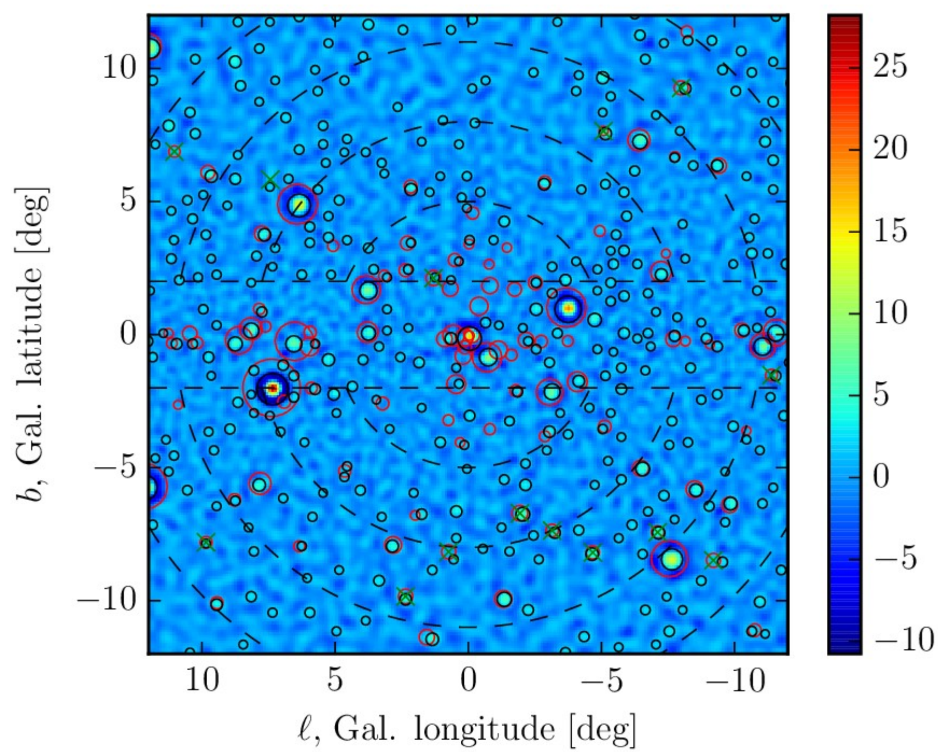
- Extract signal-to-noise ratio of peaks

$$\mathcal{S}(\Omega) = \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega)}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\Omega)}}$$

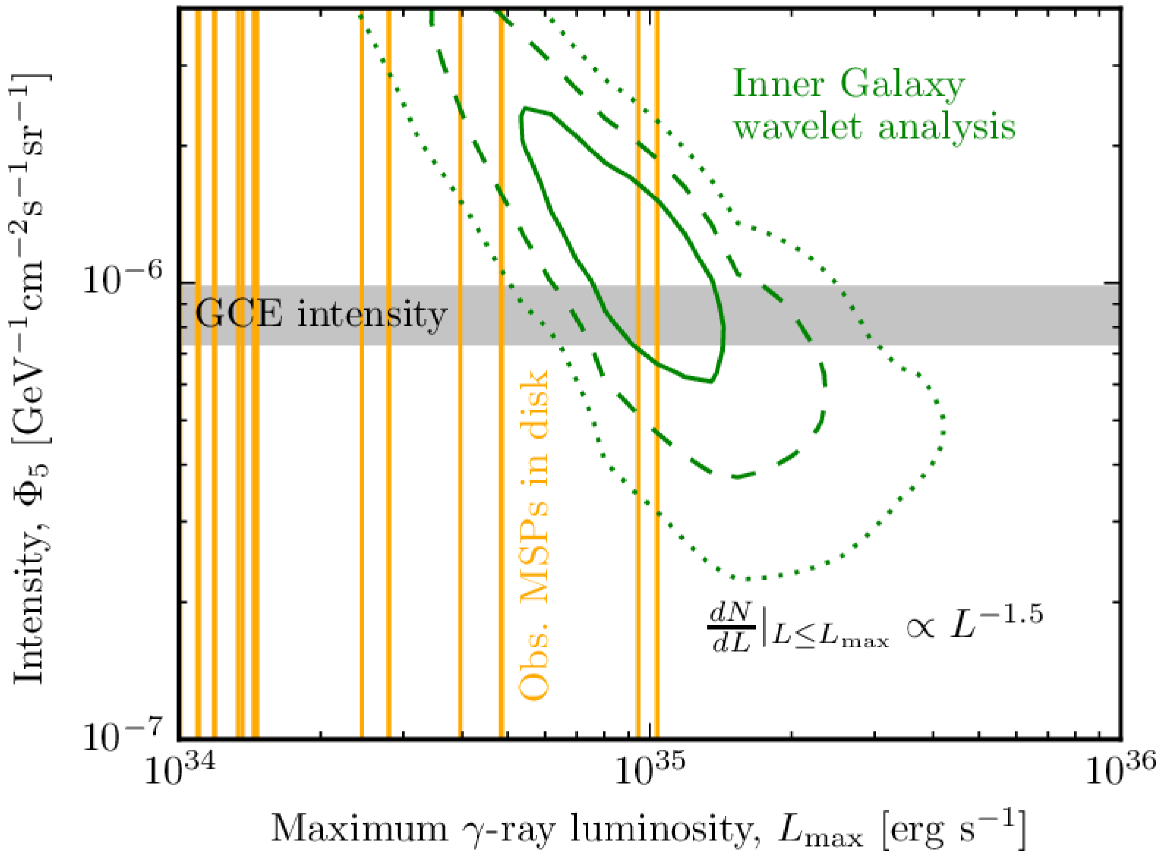
- Analyze statistics of these SNR peaks



Gonzales-Nuevo et al., 2006



Best-fit contours agree with MSP expectations



List of unassociated 3FGL sources with spectrum compatible with MSPs:

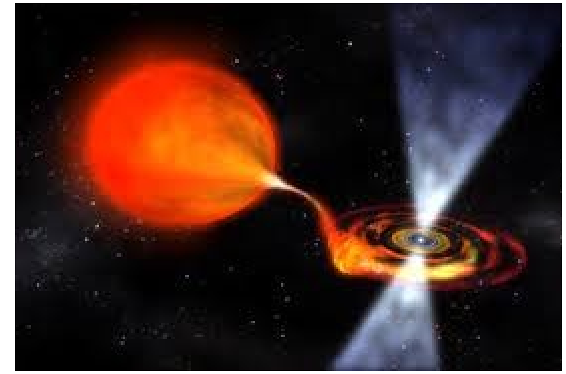
3FGL Name	ℓ [°]	b [°]	χ^2/dof	$\sqrt{TS}$	$\mathcal{S}$
J1649.6-3007	-7.99	9.27	1.07	5.57	3.68
J1703.6-2850	-5.08	7.65	0.48	2.38	4.24
J1740.5-2642	1.30	2.12	0.37	6.37	2.15
J1740.8-1933	7.43	5.83	0.77	1.89	2.11
J1744.8-1557	11.03	6.88	0.40	3.69	1.96
J1758.8-4108	-9.21	-8.48	0.90	5.56	2.91
J1759.2-3848	-7.11	-7.43	0.35	4.64	4.36
J1808.3-3357	-1.94	-6.71	0.40	6.94	5.46
J1808.4-3519	-3.15	-7.36	0.41	4.55	3.51
J1808.4-3703	-4.68	-8.19	0.22	4.95	4.45
J1820.4-3217	0.74	-8.17	1.04	5.74	2.32
J1830.8-3136	2.35	-9.84	0.54	5.92	3.76
J1837.3-2403	9.85	-7.81	0.28	4.03	2.16

This is not a proof that the GCE is due to millisecond pulsars, but it makes this scenario much more likely. There are a number of MSP-like unassociated sources towards the inner Galaxy that could be the "tip of the iceberg" of the O(1000) MSPs required to explain the excess emission.

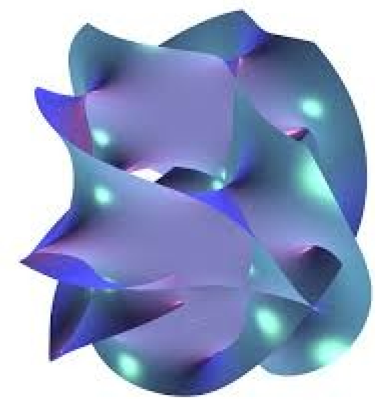
→ Confirmation of these unassociated 3FGL sources being MSPs in the bulge region will be likely decisive!

Many open questions

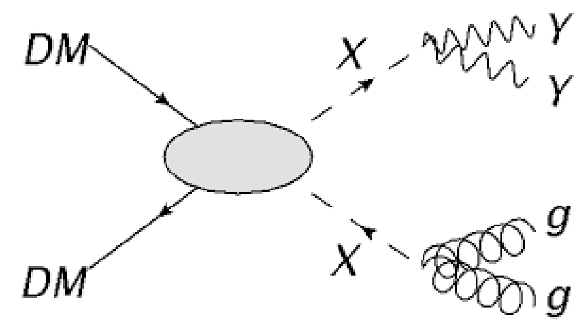
Milli-second pulsars
- Population studies and modeling
- Searches for unresolved gamma-ray point sources [Fermi-LAT, Gamma-400, AstroGam, Pangu]
- X-ray & radio observations



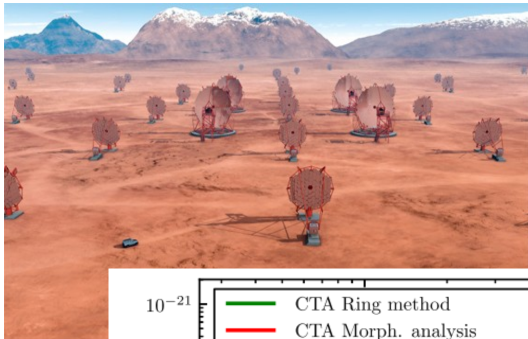
Non-standard diffusion models
- Modeling of anisotropic diffusion, convective winds
- Searches for synchrotron emission & Bremsstrahlung

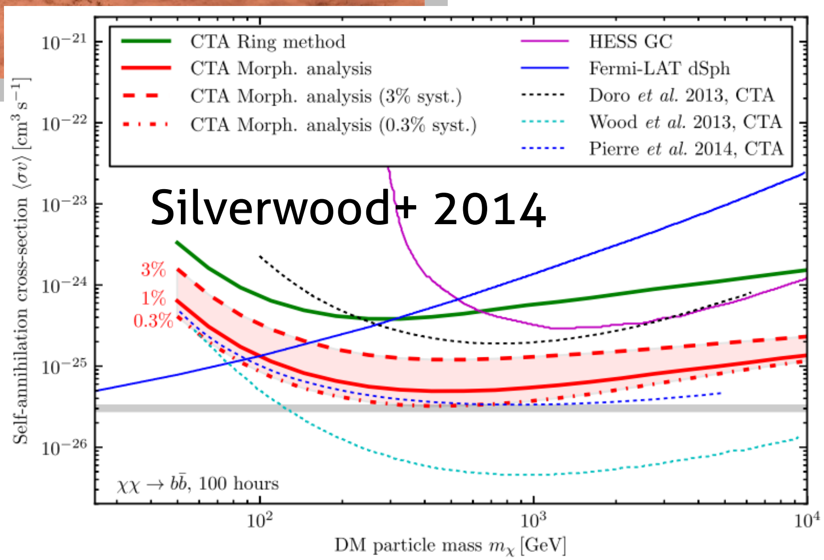


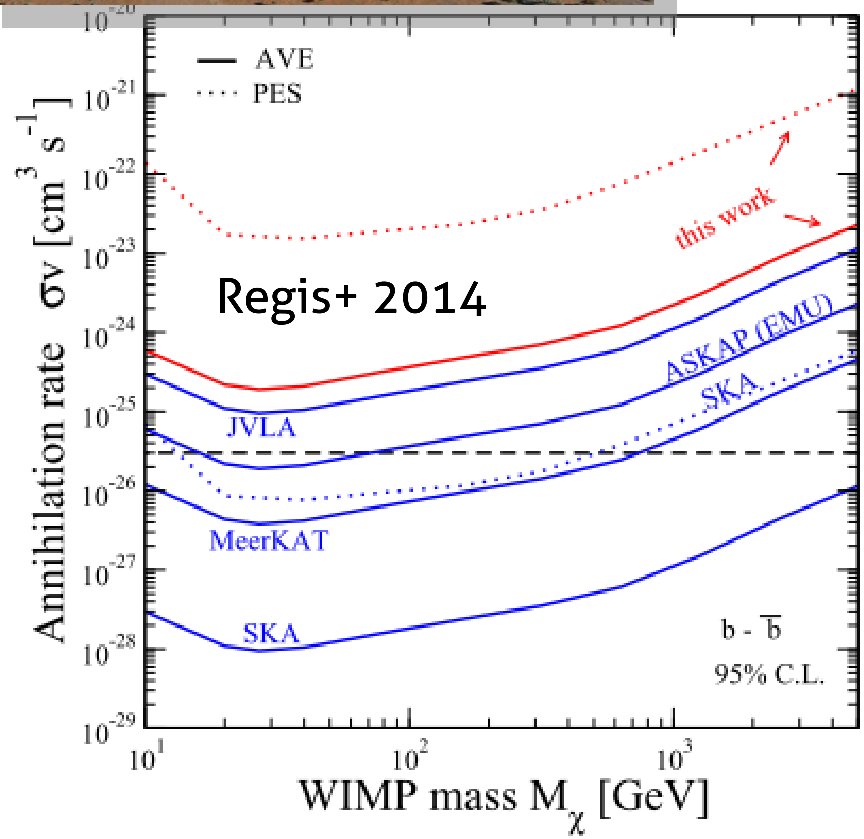
Corroborating evidence for dark matter annihilation
- Gamma-ray observations of dwarf spheroidals
- Radio observations of dwarf spheroidals [e.g. Regis+ 2014]
- Searches with anti-protons
- Direct searches & collider searches



Indirect detection prospects for the next years

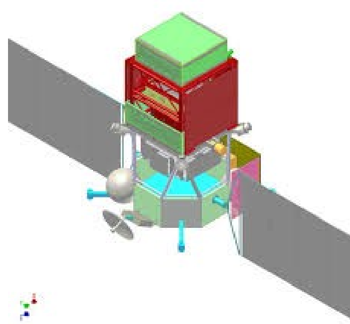






Gamma-ray satellite experiments
- GAMMA-400 (similar to Fermi)
- PANGU (focus on low energies)
- AstroGam

→ Help to clarify GC excess



Conclusions

- Indirect searches for WIMPs are
  - Promising: immediate connection to WIMP production in the early Universe → "guaranteed" signal
  - Challenging: astrophysical backgrounds and dark matter model uncertainties are large, *but not arbitrary*

- Upper limits from anti-protons, gamma-ray observations of dwarf spheroidals and line searches

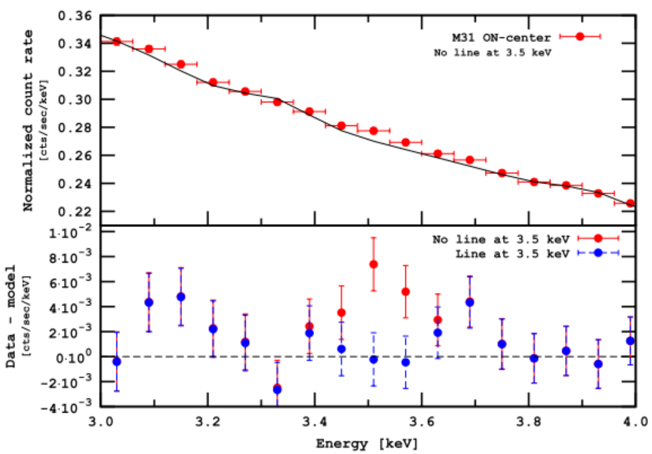
- Fermi Galactic center excess
  - The excess emission can be very well described and quantified using a PCA of residuals in the disk
  - It is the most "vanilla" signal candidate so far
  - Leptonic outbursts require drastic tuning to explain the excess
  - First indications for the MSP interpretation!

- Outlook: multi-wavelength searches, corroborating evidence from colliders and/or direct searches, theoretical studies, …

Thank you!

Backup

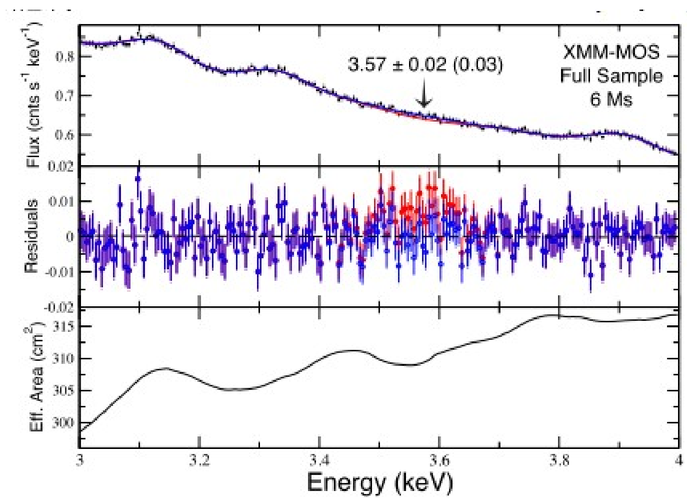
A 3.5 keV line from decaying DM?



Boyarsky et al. 2014

- Unidentified line in M31 and Perseus cluster

$$E = 3.52 \pm 0.02\,\mathrm{keV}$$



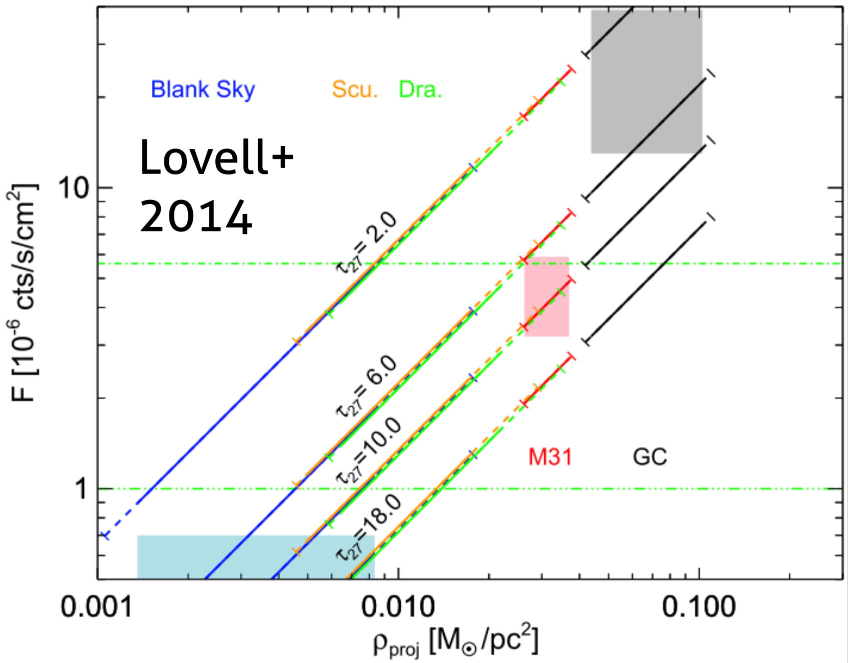
Bulbul et al. 2014

- Unidentified line in stacked XMM spectrum of 73 galaxy clusters
- Too bright in Perseus?

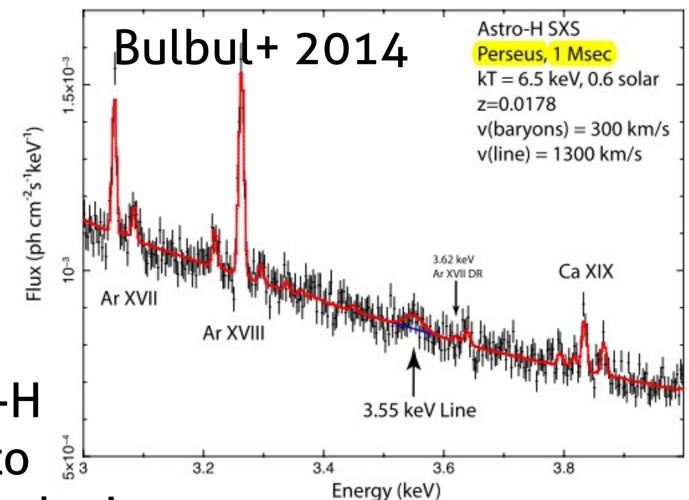
$$E = 3.56 \pm 0.04\,\mathrm{keV}$$

Yes	**No** (no corroborating evidence in other sources)
Bulbul+ 2014 & Boyarsky+ 2014	Jeltema & Profumo 2014 (Potassium?)
	Carlson+ 2014 (GC, morphology)
	Anderson+ 2014 (stacked galaxies)
	Malyshev+ 2014 (stacked dwarfs)

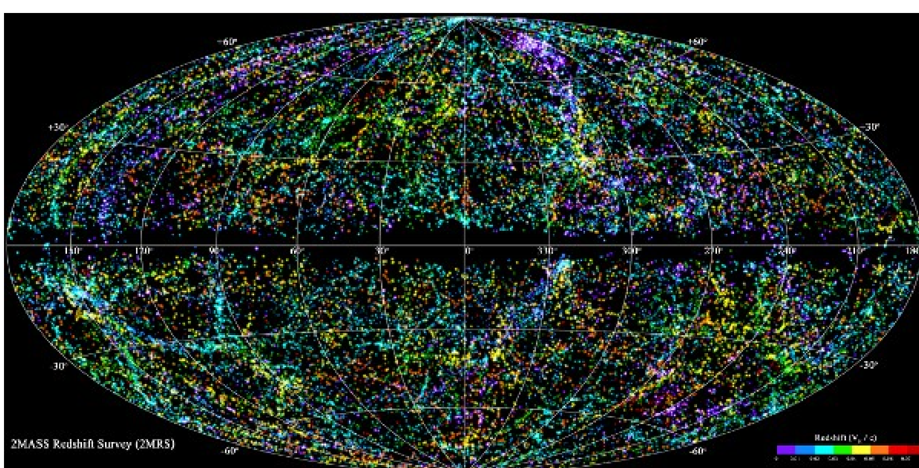
XMM-Newton, Astro-H and eROSITA



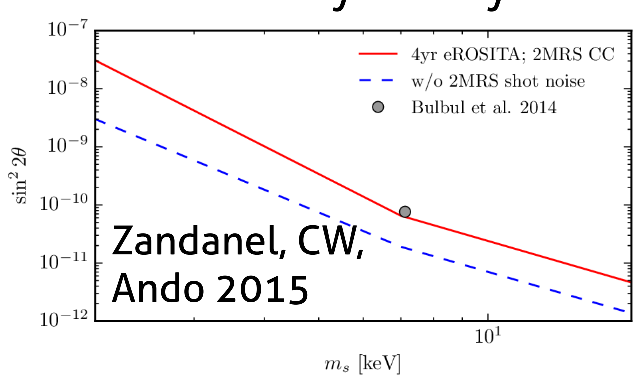
Near future: ~1Msec of XMM-Newton data on the Draco dSph. Good chance that this already settles the issue. Data is taken now.



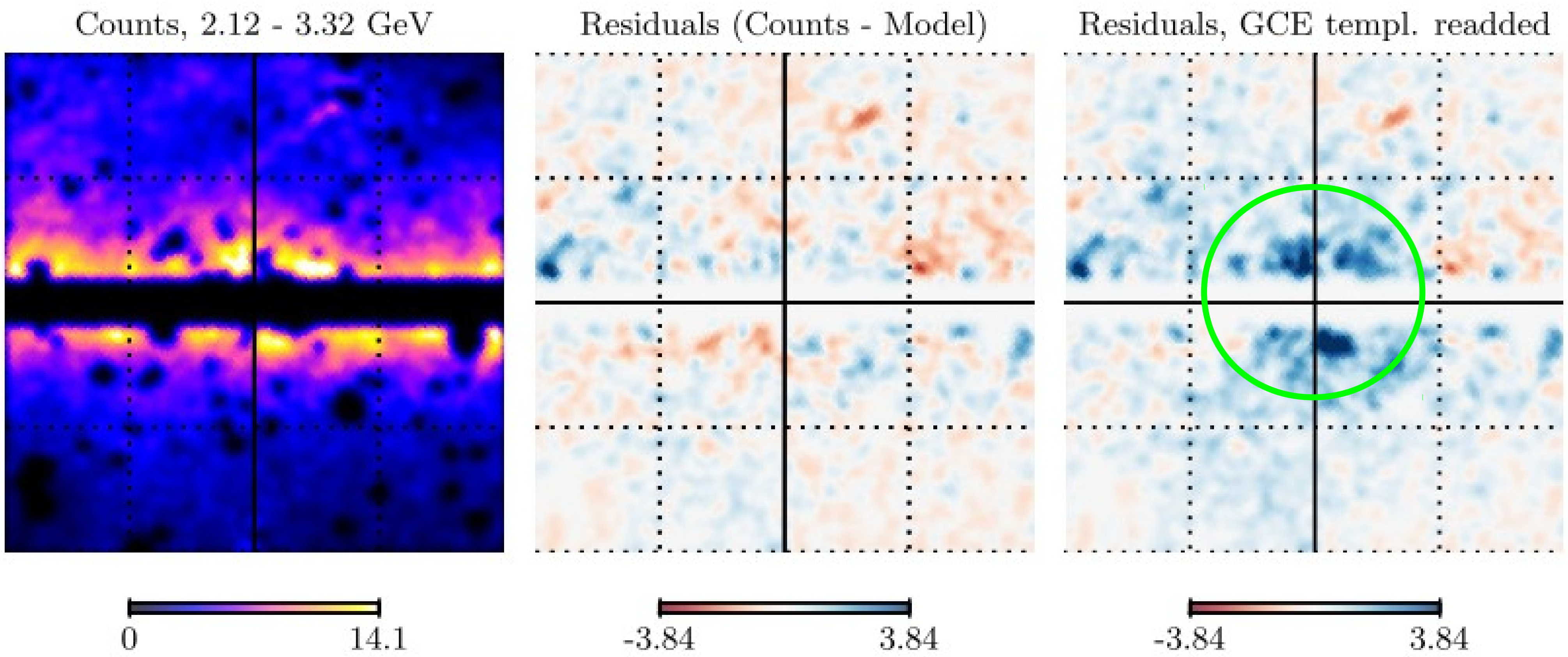
Mid-term: Astro-H should be able to resolve line-broadening



Long-term: Cross-correlations between eROSITA full-sky survey and DM tracers.

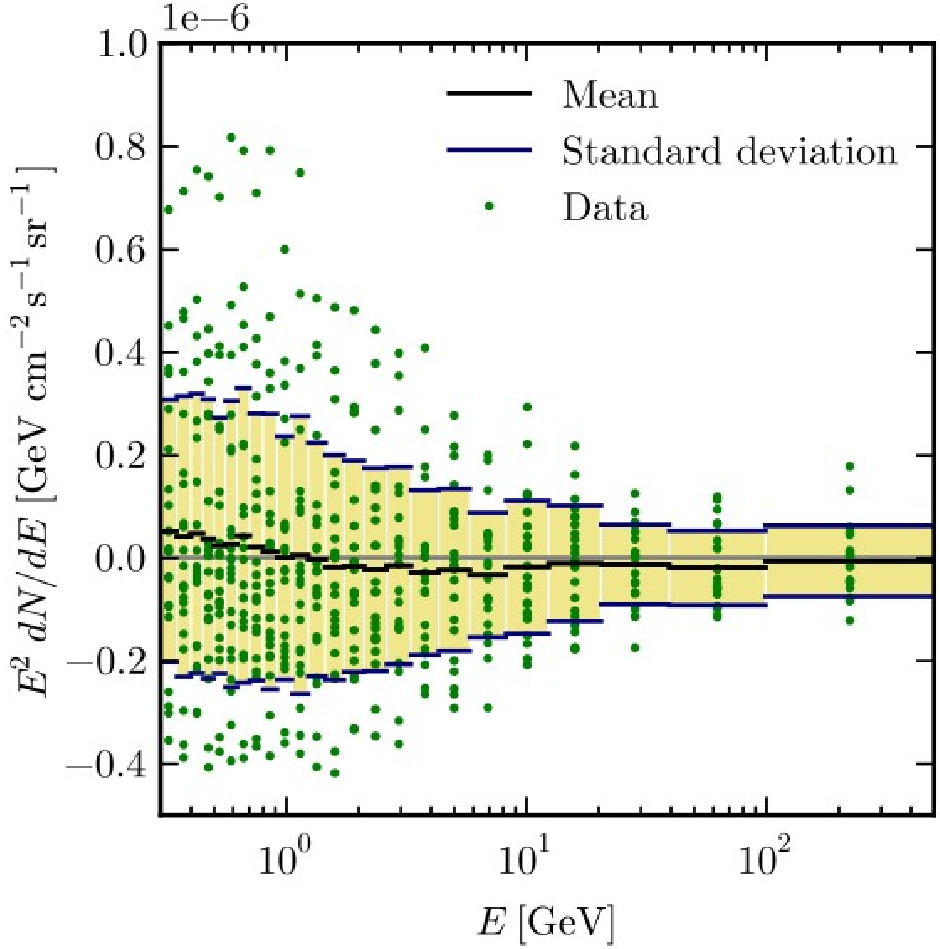


Results I: Typical residuals after foreground subtraction



- Left: Point source mask clearly visible
- Middle: Residuals at the level of <20% are observed
- Right: Readding the DM template clearly shows an extended excess around the GC

Covariance matrix of residual spectra



Residuals seen in the 24 energy bins and 22 test regions define a 24x24 covariance matrix:

$$\Sigma_{ij,\,\mathrm{mod}} = \left\langle \frac{dN}{dE_i}\frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$

i, j = 1, …, 24; averaged over 22 test regions

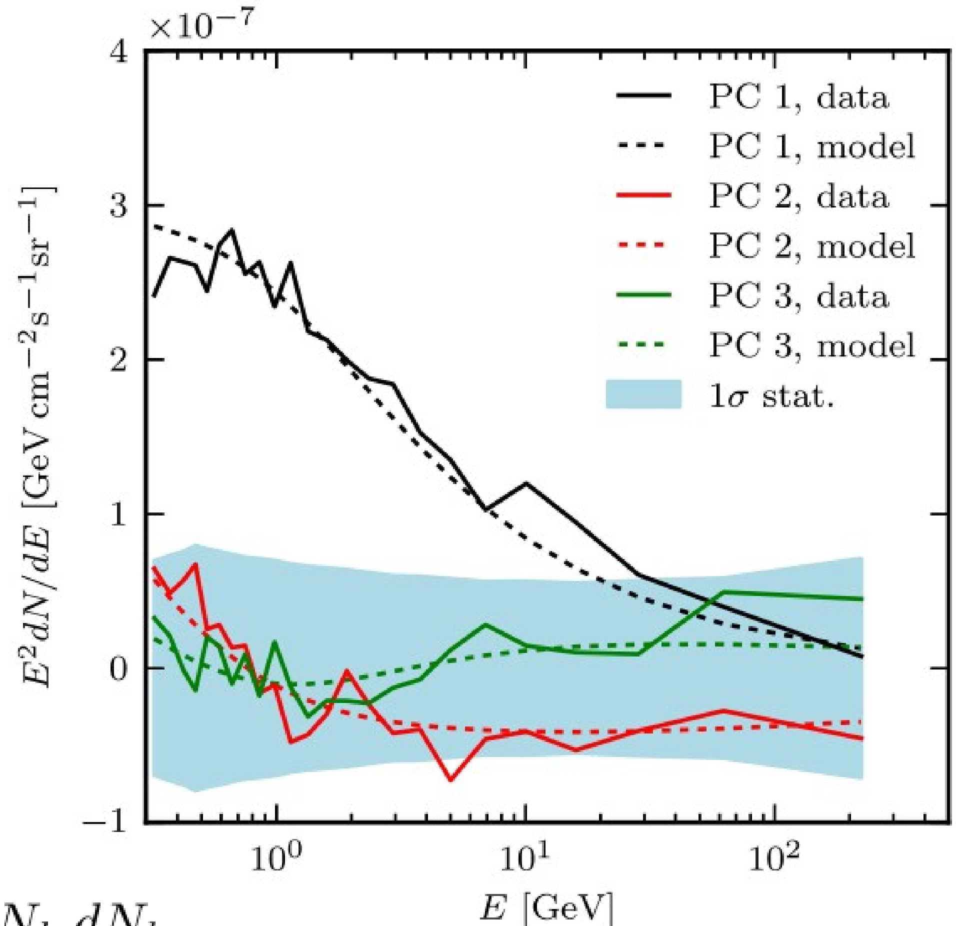
Principal component analysis

This can be understood in terms of small variations in the ICS and pi0 backgrounds.

Variations in true ICS, pi0 flux:

$$\frac{dN}{dE_i} \to \frac{dN}{dE_i}(1+\delta\alpha)E_i^{-\delta\gamma}$$

Corresponding over/undersubtraction is partially absorbed by GCE template



Solid lines: measured
Dashed lines: model

$$\Sigma_{ij,\,\mathrm{mod}} \simeq \sum_k \left(\Delta\alpha_k^2 + \Delta\gamma_k^2 \ln\frac{E_i}{E_{\mathrm{ref}}}\ln\frac{E_j}{E_{\mathrm{ref}}}\right)\frac{dN_k}{dE_i}\frac{dN_k}{dE_j}$$

$$k = \mathrm{ICS}, \pi_0$$

Normalization error
<3% (from fit)

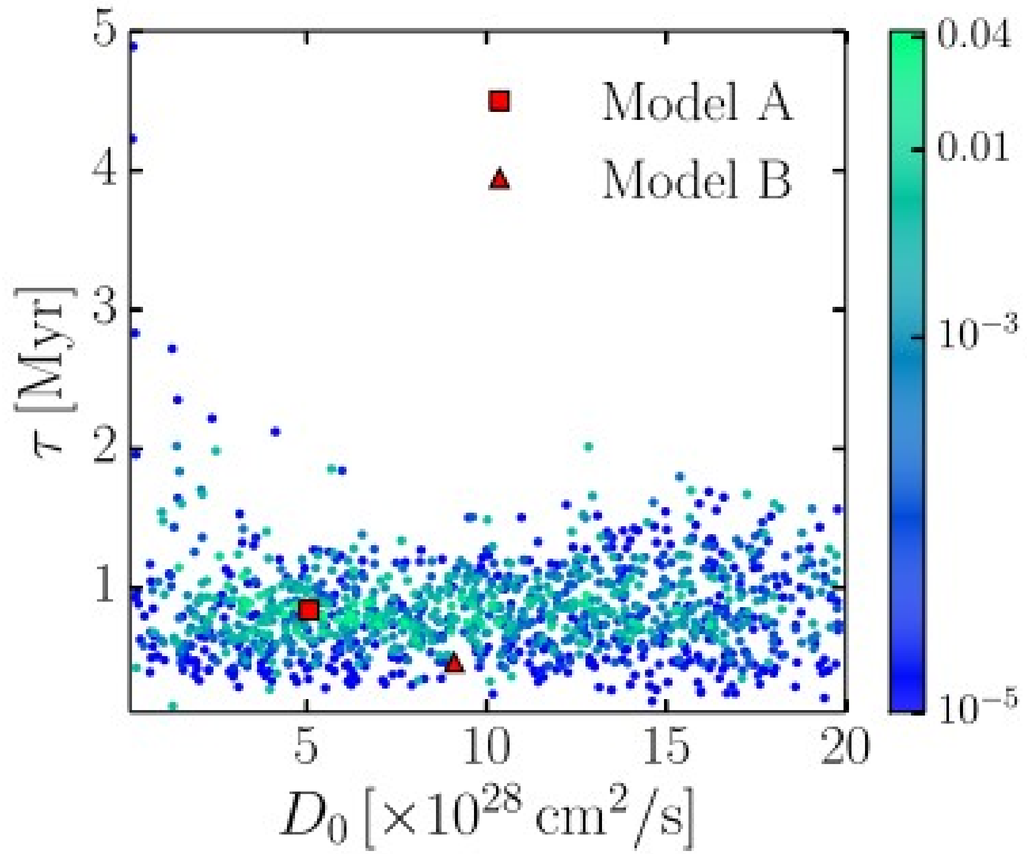
Spectral slope error
<0.01 (from fit)

Systematic scan for one-burst solutions

[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Starting point
- Multinest scan over model with leptonic bursts
- Free injection indices, normalization and diffusion parameters

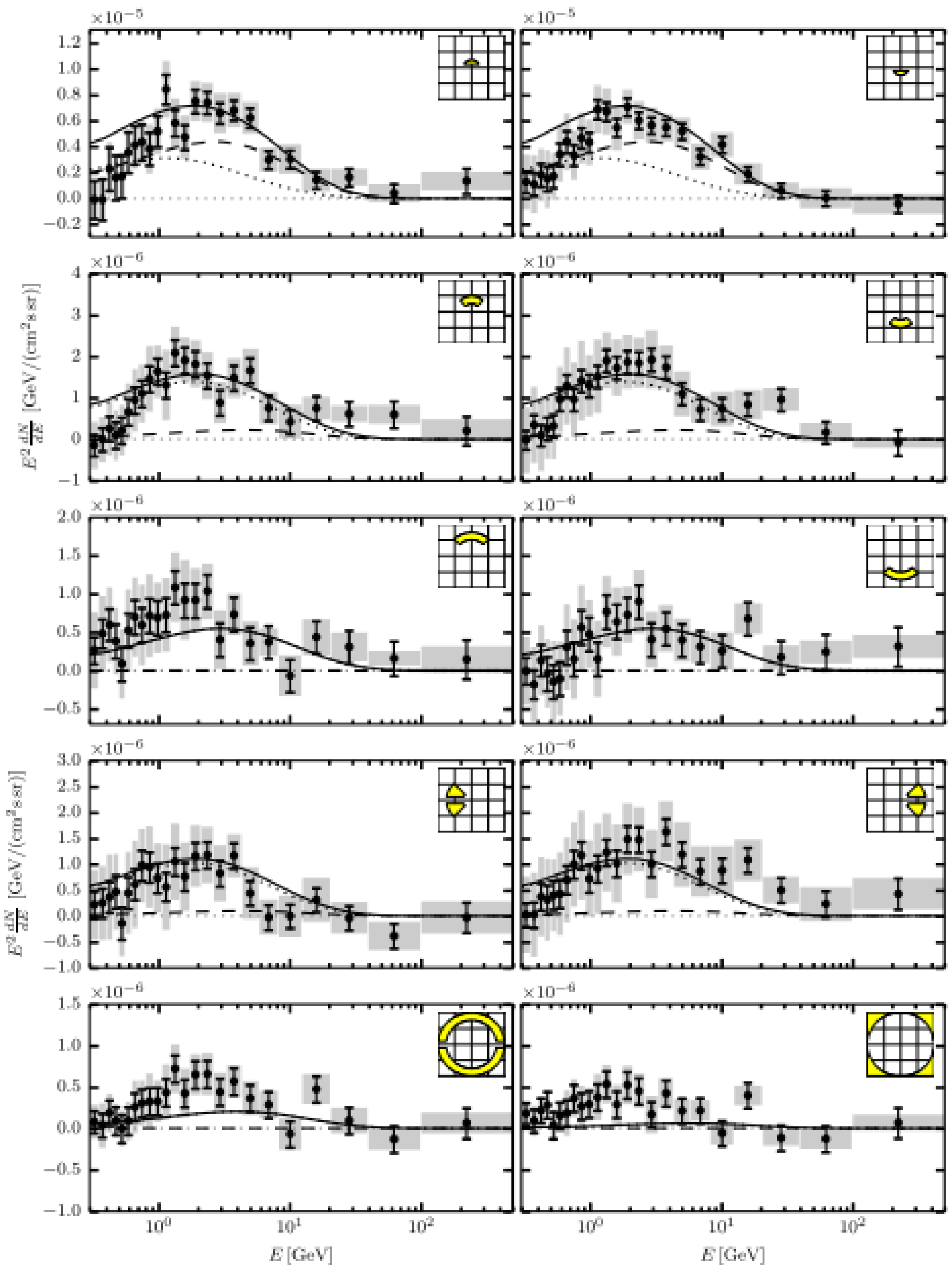
Parameter	Units	Range	Prior
α		1–3	lin
δ		0.1–1.0	lin
D_0	$10^{28}\,\mathrm{cm}^2/\mathrm{s}$	0.1–20	lin
D_{zz}/D_{xx}		0.1–10	log
v_A	km/s	0–200	lin
τ	Myr	0.1–5	lin



$$\frac{dN_e}{dE_e} = \mathcal{N}\, E_e^{-\alpha}\, \exp\{-E_e/E_{\mathrm{cut}}\}$$

$$\chi^2 = \sum_{i=1}^{10} \sum_{j,k=1}^{24} (d_{ij} - \mu_{ij})(\Sigma^i_{jk})^{-1}(d_{ik} - \mu_{ik})$$

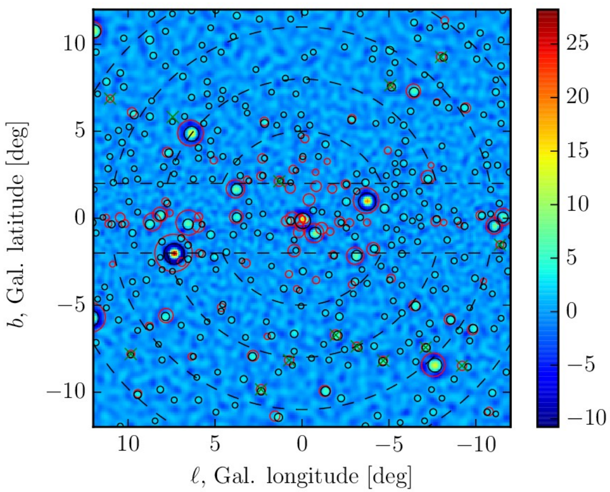
Two leptonic bursts??



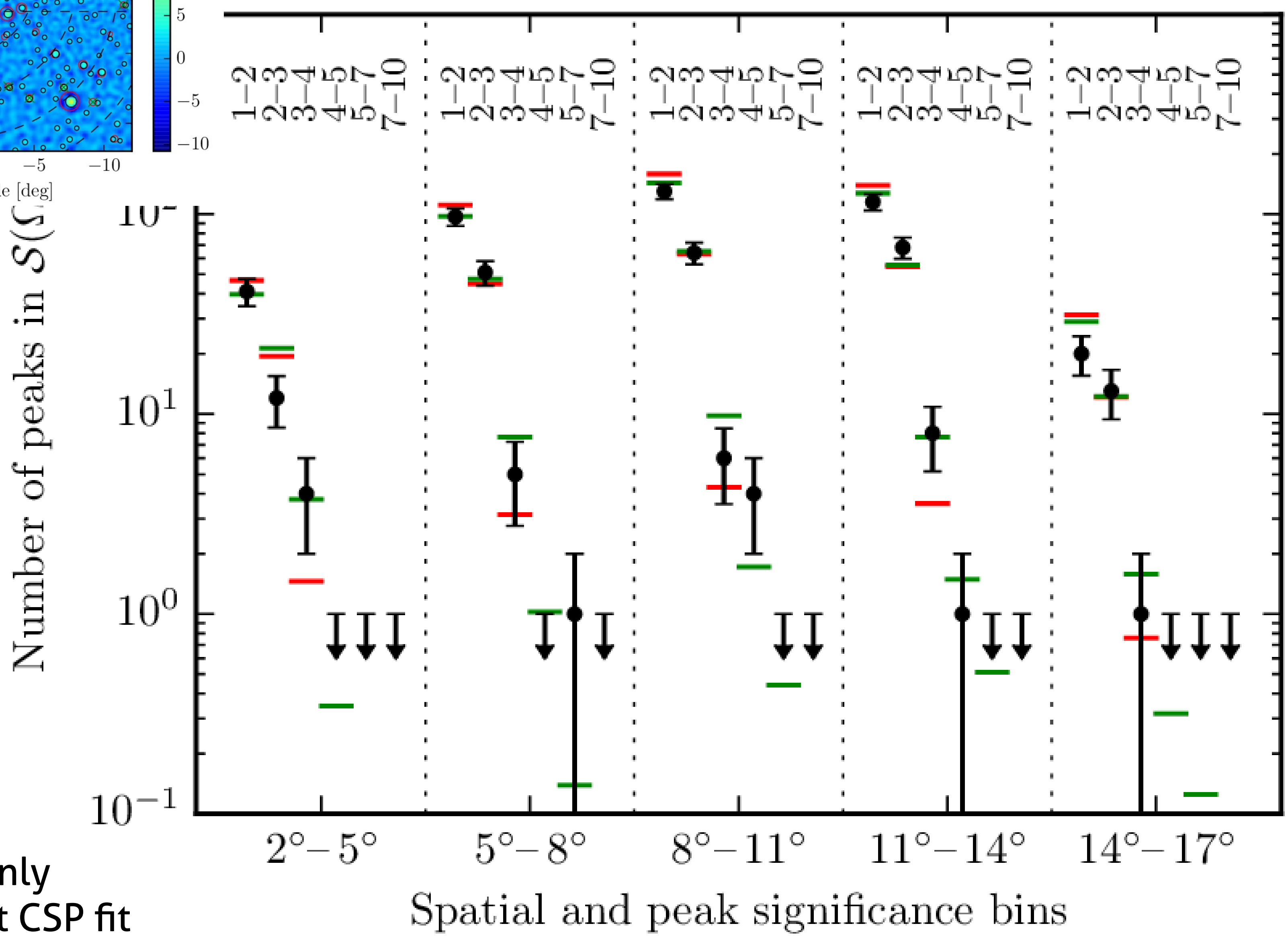
Parameter	Model A	Model B	Model C
α_1	1.2	2.0	1.1
α_2	NA	NA	1.0
$E_{\rm cut,1}$	1 TeV	1 TeV	20 GeV
$E_{\rm cut,2}$	NA	NA	60 GeV
τ_1 (Myr)	0.83	0.46	0.1
τ_2 (Myr)	NA	NA	1.0
N_1 (10^{51} erg)	2.89	9.87	0.1
N_2 (10^{51} erg)	NA	NA	0.88
δ	0.20	0.23	0.3
D_0 (10^{28} cm^2/s)	5.08	9.12	9.0
D_{zz}/D_{xx}	1.12	0.87	NA
v_A (km/s)	176	122	150
B_0 (μG)	11.5	11.5	11.7
r_c (kpc)	10.0	10.0	10.0
z_c (kpc)	2.0	2.0	0.5
dv_c/dz (km/s/kpc)	0.0	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0	1.8, 0.8
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)	261 (0.14)

[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Histogram of peaks



$$\mathcal{L} = \prod_{i=1}^{n_r} \prod_{j=1}^{n_s} \mathcal{P}(c_{ij} | \mu_{ij}(L_{\max}, \Phi_5))$$

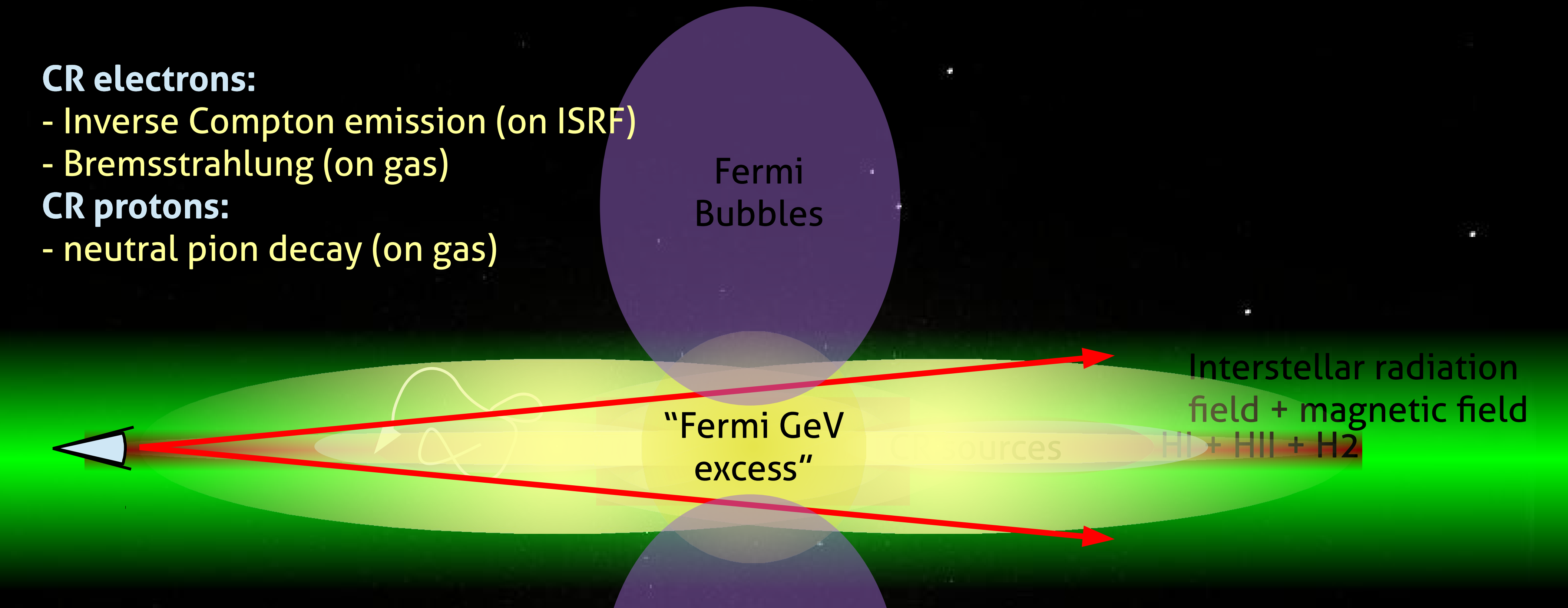


Red: diffuse only
Green: best-fit CSP fit

The Problem's Geometry:
Cartoon of the Milky Way in diffuse gamma rays

CR electrons:
- Inverse Compton emission (on ISRF)
- Bremsstrahlung (on gas)

CR protons:
- neutral pion decay (on gas)



Emissivity along the line-of-sight: